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# Canadian Journal of Research

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## THE EFFECT OF SORBED WATER ON THE PHYSICAL PROPERTIES OF ASBESTOS AND OTHER FIBRES, WITH SPECIAL REFERENCE TO RESILIENCE[1]

BY L. M. PIDGEON[2] AND A. VAN WINSEN[3]

### Abstract

It has been shown that relative humidity exerts a definite effect on the physical properties of a mass of asbestos fibre. A special apparatus has been devised in which a mass of fibre may be compressed in such a way that the volume, pressure and relative humidity of the sample are known at any time. The effect of sorbed water on asbestos is to increase the apparent density and to decrease compressibility and resiliency. It has been assumed that the major factor which controls these characteristics is the fact that sorption of water affects the surface in such manner that the slippage of the fibres over one another is facilitated. Since no fibre unit is experimentally obtainable in the case of asbestos, the fibre bundle must be considered and the stiffness of such a bundle depends on the ease of slippage of its components and hence on relative humidity. This fact is of prime importance in the testing of asbestos where humidity will exert a direct effect on the screen test.

Cotton and wool fibres have been examined, and a definite effect of humidity demonstrated. Certain theoretical speculations in the case of cotton have been put forward.

### Introduction

It has been known that sorbed moisture exerts a definite effect on the physical properties of fibrous materials, such as cotton; the effect of sorption on these organic fibres has generally been attributed to swelling and attendant phenomena. In the case of inorganic fibres such as asbestos, on the other hand, the physical effects of sorbed moisture are not as obvious, and until recently their existence had not been recognized. One of the writers (A.v.W) found that relative humidity exerted a definite effect on the physical properties of asbestos fibre. Screen test of the fibre showed definite variations and the apparent density seemed to be affected by humidity. In view of the practical importance of this observation, it seemed desirable to obtain quantitative data on the subject. The present research deals largely with asbestos fibre but has been extended to a limited degree to cotton and wool.

[1] *Manuscript received October 23, 1933.*
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An examination of the effects of sorbed moisture entails first, measurement of the amount of moisture sorbed under various conditions of relative humidity, and second, a measurement of the effect of this moisture on the physical properties of the fibres. The first part has already been carried out (2); the present paper describes measurements made on the second.

The physical properties of a fibre which control the behavior of a fibrous mass are: (*a*) structural, such as section modulus, elasticity, resiliency and shape; (*b*) surface, including coefficient of friction and contour, which influence the mutual effects of the fibres such as slippage and interlocking.

In order to determine the effect of humidity on these properties it is necessary to examine first the individual fibres and then their mutual effect as manifested in a mass of fibres. With asbestos, however, the problem is complicated by the fact that no fibre unit such as appears in the case of cotton and other organic fibres is obtainable. It is possible to subdivide asbestos fibres down to the limit of the microscope and even then there is no reason to believe that the process may not be continued. Hence the first part of the ideal research is beyond reach of present knowledge and technique, and it becomes necessary to deal with the fibres *en masse*.

One of the more obvious properties of a mass of fibres is the ability to be compressed and to return in some measure to the original volume when pressure is released. The amount of recovery after compression may be termed resiliency if the broader use of the word is accepted (*i.e.*, resiliency is the potential energy due to strain, without limitation as to exceeding the elastic limit). This property is determined by the structural and surface factors referred to above. Sorbed water may affect either or both of these, but in any case the change will be detectable as a change in the resiliency of the mass of fibres. Hence by measuring this resiliency at different humidities, quantitative data regarding the physical effects of sorbed water are obtainable. This procedure has been followed in experiments to be described.

## Apparatus and Methods

An apparatus is required to compress a mass of fibres in such a way that the volume, pressure and relative humidity are known at any time. The method which has been followed consists of enclosing the fibre in a rubber bulb which is then subjected to a hydraulic pressure. A rubber bulb was previously used by Winson (5) when working with wool, but in his apparatus the sample was compressed by gas pressure. The change in gas pressure around the sample during compression offered a means of calculating the volume at any pressure from the gas law. This fact renders the apparatus unsuitable for the present use as changes in pressure in the gas surrounding the sample would result in changes in relative humidity. This difficulty has been removed in the apparatus to be described, in which the compression of the bulb is effected by the addition of a measured amount of liquid to a closed system. The volume and pressure may be directly and accurately measured. The pressure of the gas surrounding the fibres is unchanged during the compression, hence humidity remains constant.

## Apparatus

The apparatus is illustrated in Fig. 1. A rubber bulb *A* containing the sample is placed on a brass tube *D* opening to the atmosphere through a conditioning chamber. The bulb is placed in a glass jar *B* which is fitted with brass end plates and tension bolts. A liquid-tight seal is obtained with a rubber gasket, fitted to the ground rim of the jar. This part of the apparatus is connected by suitable tubes to the volume and pressure metering part as shown in the diagram. The metering part consists of a mercury manometer *G*, designed to produce minimum volume changes and a burette for adding known amounts of liquid. The liquid was forced into the jar by displacement with mercury. Water has been found to be satisfactory though any other chemically inert liquid would function equally well.

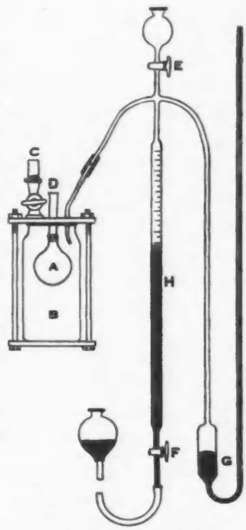

FIG. 1. *Diagram of compression apparatus.*

## Method

*a. Preparation and loading of samples.* In the initial experiments the asbestos fibre was inserted in the bulb by hand, using blunt nosed forceps. A fine glass tube ran in through the neck of the bulb and extended to the opposite extremity. Air at known humidity was passed through this tube in order to condition the fibre. It was found that with asbestos, the gas flow through the fibre was localized, most of the flow apparently taking place in a channel around the inlet tube, hence other means of conditioning the fibre were adopted. A glass tube 3 cm. in diameter was drawn down in a long taper to a diameter of 1.5 cm. The fibre was placed in this tube and air at known humidity passed through for 24 hr. The rubber bulb was then fitted over the small end of this tube, and partly inflated by pumping conditioned air into the tube, the pressure required to inflate the bulb being 3-4 cm. of mercury. The asbestos fibre was then tapped into the bulb after which the pressure was slowly released while the bulb was tapped gently. In this manner a very uniform type of packing was obtainable, the apparent density of dry and conditioned fibre giving a close check between different loadings.

This loading technique could not be used with cotton and wool owing to the nature of the fibres. The dry samples were prepared in an oven at 105°C., and subsequently loaded into the bulb by hand using forceps, the bulb being placed in a desiccator into which a current of dry air was passed. The higher humidities were treated in a similar way in a stream of conditioned air. It would probably be feasible to condition the fibres of cotton and wool by passing conditioned air through the loaded bulb.

*b. Manipulation of apparatus.* After filling as described above, the rubber bulb is removed from the glass and the initial volume is obtained by water

displacement. The bulb is then fitted to the apparatus as illustrated, after which the apparatus is assembled and the end plates bolted.

The jar *B* is filled with water and care is taken to remove all air bubbles. The jar is then attached to the metering portion of the apparatus. Volume readings on the burette and corresponding pressure readings are taken. The compression is achieved by adding mercury to the apparatus through the lower stopcock *F*. The pressure may be released in a regular way by removing the previously added volumes. The rate at which equilibrium is established after displacement may be measured by taking pressure readings against time.

## Results

Typical results appear in Tables I to VII. The volume of the sample is listed on the left with the corresponding pressure during each cycle of pressure and release appearing opposite. The initial volume is obtained by water displacement, and the subsequent volumes are based on it and include the volume change as read on the burette. The pressure readings were taken at a set time (15 sec.) after the corresponding volume change. Several runs were carried out in which 10 min. or more elapsed between each reading: though some pressure change took place during this time, the essential nature of the curves was unchanged, hence the shorter times were adopted for reasons of convenience. It was possible to check the results reasonably well between different runs. Small errors in the measurement of the original volume simply shift the whole curve without altering its shape. A standard maximum pressure of 48 cm. of mercury has been chosen. A number of experiments

TABLE I

Pressure-volume relation of asbestos fibre (30 gm.) dried in air for 24 hr.

| Vol. cc. | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | | Cycle 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. |
| 81 | 0.0 | | | | | | | | | |
| 75 | 4.8 | | | | | | | | | |
| 69 | 9.8 | | | | | | | | | |
| 63 | 18.0 | | | | | | | | | |
| 61 | 21.6 | 0.1 | 3.2 | 0.1 | 1.2 | | | | | |
| 60 | 23.8 | 0.3 | 5.6 | 0.2 | 3.1 | 0.0 | — | −0.1 | — | −0.2 |
| 59 | 26.1 | 0.9 | 8.8 | 0.7 | 5.2 | 0.3 | 2.5 | 0.2 | 2.1 | 0.1 |
| 58 | 29.0 | 1.7 | 12.6 | 1.6 | 7.8 | 0.9 | 4.6 | 0.6 | 4.0 | 0.4 |
| 57 | 31.6 | 3.3 | 17.7 | 3.0 | 11.9 | 1.8 | 8.1 | 1.3 | 7.0 | 1.1 |
| 56 | 35.0 | 5.7 | 24.4 | 5.6 | 16.9 | 3.8 | 12.6 | 3.1 | 10.8 | 2.3 |
| 55 | 38.4 | 9.5 | 31.4 | 9.8 | 24.0 | 6.7 | 18.6 | 5.5 | 16.2 | 4.5 |
| 54 | 42.0 | 16.8 | 39.6 | 19.0 | 32.1 | 13.1 | 26.5 | 10.2 | 23.8 | 8.6 |
| 53 | 46.1 | 33.1 | 47.0 | 39.3 | 42.0 | 26.8 | 37.0 | 20.8 | 33.2 | 16.6 |
| 52.8 | — | — | 48.0 | — | — | — | — | — | — | — |
| 52.6 | 48.0 | — | — | — | — | — | — | — | — | — |
| 52.3 | — | — | — | — | 48.0 | — | — | — | — | — |
| 52 | — | — | — | — | — | — | 48.0 | — | 45.2 | 36.5 |
| 51.7 | — | — | — | — | — | — | — | — | 48.0 | — |

at lower pressures were carried out but, while they showed the same general effects, the curves were not quite as clear as at the higher pressure. The upper pressure limit of the present apparatus was 75 cm. of mercury.

The samples used in these experiments were of the following varieties:

*Asbestos.* This fibre was a well-fiberized standard mill product of the chrysotile variety obtained from one of the mines in the Thetford district in the province of Quebec, classified as 4M fibre and having a Quebec Standard Test of 0.0—4.0—8.0—4.0.

*Cotton.* Unbleached cotton wool, short fibre.

*Wool.* Scoured Colonial 56's.

TABLE II

PRESSURE-VOLUME RELATION OF ASBESTOS FIBRE (30 gm.) IN AIR AT 95% RELATIVE HUMIDITY FOR 16 HR. SORBED WATER 3.0% BY WEIGHT

| Vol. cc. | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | | Cycle 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. |
| 70 | 0.0 | | | | | | | | | |
| 64 | 9.4 | | | | | | | | | |
| 60 | 14.6 | | | | | | | | | |
| 56 | 21.8 | | | | | | | | | |
| 54 | 26.8 | 0.0 | | | | | | | | |
| 53 | 29.4 | 0.2 | 2.9 | 0.0 | | | | | | |
| 52 | 32.5 | 1.2 | 7.1 | 0.3 | 2.7 | 0.1 | | 0.0 | | 0.0 |
| 51 | 35.7 | 3.5 | 13.2 | 1.3 | 7.1 | 0.7 | 4.5 | 0.4 | 3.4 | 0.3 |
| 50 | 39.1 | 7.6 | 21.1 | 3.9 | 14.0 | 2.8 | 10.5 | 2.0 | 8.4 | 1.4 |
| 49 | 43.5 | 18.3 | 31.8 | 9.4 | 23.3 | 7.1 | 18.8 | 5.5 | 16.3 | 4.7 |
| 48 | 47.6 | | 43.1 | 23.6 | 35.6 | 18.3 | 30.8 | 15.0 | 27.2 | 12.2 |
| 47.3 | | | 48.0 | | — | | — | — | — | |
| 47 | | | | | 48.1 | | 45.6 | 39.6 | 43.0 | 33.0 |
| 46.8 | | | | | | | 48.0 | | — | |
| 46.6 | | | | | | | | | 48.0 | |

TABLE III

PRESSURE-VOLUME RELATION OF ASBESTOS FIBRE (30 gm.) IN AIR AT 60% RELATIVE HUMIDITY. SORBED WATER 1.3% BY WEIGHT

| Vol. cc. | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | |
|---|---|---|---|---|---|---|---|---|
| | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. |
| 73 | 0.0 | | | | | | | |
| 68 | 6.1 | | | | | | | |
| 62 | 11.1 | | | | | | | |
| 56 | 20.1 | | | | | | | |
| 55 | 22.0 | 0.0 | | | | | | |
| 54 | 24.2 | 0.3 | 3.4 | −0.1 | | | | |
| 53 | 26.7 | 1.2 | 5.0 | 0.1 | 2.5 | 0.0 | | −0.4 |
| 52 | 29.4 | 2.5 | 8.3 | 1.1 | 5.2 | 0.3 | 2.7 | 0.4 |
| 51 | 32.5 | 3.5 | 12.8 | | 7.4 | 1.2 | 5.1 | 0.8 |
| 50 | 36.0 | 6.2 | 17.0 | 3.5 | 11.3 | 2.5 | 8.0 | 1.9 |
| 49 | 39.4 | | 24.3 | 5.5 | 16.7 | 4.3 | 12.9 | 3.4 |
| 48 | 43.6 | 21.6 | 33.0 | 10.9 | 24.4 | 7.5 | 19.1 | 5.2 |
| 47.2 | 48.0 | | | | | | | |
| 47 | | | 42.0 | 22.6 | 34.5 | 15.0 | 28.1 | 11.3 |
| 46.2 | | | 48.0 | | | | | |
| 46 | | | | | 45.5 | 34.6 | 40.2 | 27.0 |
| 45.7 | | | | | 48.0 | | | |
| 45.3 | | | | | | | 48.0 | |

TABLE IV

PRESSURE-VOLUME RELATION OF UNBLEACHED COTTON FIBRES (5.0 gm.) DRIED 24 HR. AT 105°C.

| Vol. cc. | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | |
|---|---|---|---|---|---|---|---|---|
| | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. |
| 51 | 0 | | | | | | | |
| 49 | 1.6 | 0 | | | | | | |
| 47 | 3.5 | 0.3 | 0.5 | 0.0 | | −0.2 | | −0.3 |
| 45 | 5.6 | 0.6 | 1.9 | 0.5 | 1.1 | 0.3 | 0.9 | 0.2 |
| 43 | 8.0 | 1.2 | 3.5 | 1.0 | 2.7 | 0.9 | 2.4 | 0.7 |
| 41 | 10.5 | 2.5 | 5.4 | 1.9 | 4.4 | 1.5 | 4.0 | 1.6 |
| 39 | 13.2 | 3.7 | 7.5 | 3.1 | 6.3 | 2.7 | 6.0 | 2.8 |
| 37 | 16.5 | 5.2 | 10.3 | 4.5 | 8.9 | 4.9 | 8.3 | 4.0 |
| 35 | 20.2 | 7.0 | 13.6 | 6.1 | 12.0 | 5.8 | 11.4 | 5.4 |
| 33 | 24.7 | 9.8 | 18.2 | 8.7 | 16.2 | 8.0 | 14.0 | 7.5 |
| 31 | 30.1 | 13.8 | 24.0 | 12.6 | 21.9 | 11.7 | 20.8 | 11.2 |
| 29 | 37.2 | 21.6 | 31.6 | 18.7 | 29.5 | 17.0 | 28.2 | 17.0 |
| 27 | 45.4 | 36.0 | 42.0 | 31.8 | 40.2 | 28.8 | 38.4 | 27.2 |
| 26.4 | 48.0 | — | — | — | — | — | — | — |
| 26 | — | — | 48.0 | — | 46.5 | 39.8 | 45.0 | 38.0 |
| 25.7 | — | — | — | — | 48.0 | — | — | — |
| 25.5 | — | — | — | — | — | — | 48.0 | — |

TABLE V

PRESSURE-VOLUME RELATION OF UNBLEACHED COTTON FIBRES (5.0 gm.) IN AIR AT 95–97% RELATIVE HUMIDITY FOR 18 HR.

| Vol. cc. | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | |
|---|---|---|---|---|---|---|---|---|
| | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. |
| 52 | 0.3 | | | | | | | |
| 51 | 1.6 | | | | | | | |
| 50 | 2.7 | | | | | | | |
| 48 | 4.8 | | | | | | | |
| 46 | 6.6 | | | | | | | |
| 44 | 8.6 | 0.0 | | 0.0 | | | | |
| 42 | 11.1 | 0.4 | 1.6 | 0.4 | 1.2 | 0.1 | | −0.1 |
| 40 | 14.3 | 1.2 | 3.5 | 0.9 | 2.5 | 0.4 | 1.5 | 0.4 |
| 38 | 17.7 | 1.9 | 6.1 | 1.4 | 4.5 | 1.2 | 3.4 | 1.0 |
| 36 | 21.9 | 3.2 | 9.7 | 2.6 | 7.6 | 2.2 | 6.0 | 1.8 |
| 34 | 27.5 | 5.5 | 15.4 | 4.5 | 12.3 | 4.0 | 10.4 | 3.6 |
| 32 | 34.8 | 10.0 | 24.3 | 7.6 | 20.3 | 7.2 | 18.0 | 6.5 |
| 30 | 42.8 | 23.2 | 36.7 | 17.2 | 32.5 | 15.7 | 29.9 | 14.1 |
| 29 | 48.0 | | 44.2 | 29.8 | 40.2 | 26.2 | 38.2 | 23.7 |
| 28.4 | — | | 48.0 | — | — | — | — | — |
| 28.2 | — | | — | — | 48.0 | — | — | — |
| 28.0 | — | | — | — | — | — | 48.0 | — |

TABLE VI

PRESSURE-VOLUME RELATION OF WOOL (WASHED FIBRES, 35 gm.) DRIED AT 105°C.

| Vol. cc. | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | |
|---|---|---|---|---|---|---|---|---|
| | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. |
| 56 | 0.6 | | | | | | | |
| 55 | 1.7 | −0.2 | | | | | | |
| 54 | 2.7 | 0.3 | 1.1 | −0.1 | | −0.3 | | −0.4 |
| 51 | 5.2 | | 2.8 | 0.6 | 1.4 | 0.5 | 1.4 | 0.4 |
| 49 | 5.8 | 1.5 | — | — | — | — | — | — |
| 47 | 7.5 | 2.2 | 4.5 | 1.7 | 4.0 | 1.5 | 3.2 | — |
| 45 | 9.0 | 2.8 | 5.8 | — | — | — | 4.5 | 2.0 |
| 43 | 10.8 | 3.6 | 7.5 | 3.2 | 6.4 | 2.8 | — | — |
| 41 | 12.9 | 4.6 | 9.3 | — | — | — | 7.2 | 3.5 |
| 39 | 15.0 | 5.6 | 11.3 | 5.3 | 9.7 | 4.6 | — | — |
| 37 | 17.5 | 7.7 | 13.5 | 6.8 | — | — | 11.2 | 5.8 |
| 35 | 20.4 | 9.5 | 16.2 | 8.3 | 14.5 | 7.9 | — | — |
| 33 | 23.7 | 11.8 | 19.7 | 10.7 | — | — | 17.0 | 9.8 |
| 31 | 28.2 | 15.3 | 24.2 | 13.7 | 22.1 | 12.9 | — | — |
| 29 | 33.7 | 20.3 | 29.7 | 18.5 | 27.6 | 17.3 | 24.6 | 16.6 |
| 27 | 40.8 | 28.9 | 37.4 | 25.5 | 35.0 | 24.3 | — | — |
| 26 | 44.9 | 35.5 | 41.4 | 31.4 | — | — | 38.1 | 29.0 |
| 25.1 | 48.0 | — | — | — | — | — | — | — |
| 25 | — | — | 46.5 | 40.0 | 44.8 | 37.6 | — | 36 |
| 24.6 | — | — | 48.0 | — | — | — | — | — |
| 24.3 | — | — | — | | 48.0 | — | 48.0 | — |

TABLE VII

PRESSURE-VOLUME RELATION OF WOOL (5.0 gm.) IN CURRENT OF AIR AT 95% RELATIVE HUMIDITY FOR 24 HR.

| Vol. cc. | Cycle 1 | | Cycle 2 | | Cycle 3 | | Cycle 4 | |
|---|---|---|---|---|---|---|---|---|
| | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. | Comp. | Rel. |
| 54 | 0.0 | | | | | | | |
| 53 | 1.0 | | | | | | | |
| 52 | 1.6 | | | | | | | |
| 51 | 2.1 | | | | | | | |
| 49 | 3.3 | 0.0 | | | | | | |
| 47 | 4.9 | 0.1 | 1.1 | 0.0 | — | −0.2 | — | −0.2 |
| 45 | 6.2 | 0.4 | 2.3 | 0.2 | 1.3 | 0.2 | 0.8 | 0.2 |
| 43 | 7.2 | 1.0 | 3.5 | 0.7 | 2.5 | 0.4 | 2.0 | 0.4 |
| 41 | 9.0 | 1.8 | 4.9 | 1.6 | 3.7 | 1.3 | 3.0 | 0.7 |
| 39 | 11.7 | 2.7 | 6.7 | 1.8 | 5.1 | 1.8 | 4.4 | 1.5 |
| 37 | 13.4 | 3.4 | 8.6 | 3.0 | 7.1 | 2.6 | 6.0 | 2.6 |
| 35 | 16.3 | 4.8 | 11.2 | 4.2 | 9.5 | 4.0 | 8.3 | 3.7 |
| 33 | 20.0 | 6.4 | 14.9 | 6.0 | 13.0 | 5.2 | 11.6 | 5.1 |
| 31 | 24.8 | 8.8 | 19.7 | 8.8 | 17.5 | 7.9 | 16.1 | 7.2 |
| 29 | 31.2 | 13.7 | 26.5 | 12.7 | 24.0 | 12.0 | 22.5 | 11.0 |
| 27 | 40.1 | 22.2 | 35.4 | 21.5 | 34.0 | — | 31.8 | 18.8 |
| 26 | 45.0 | 32.2 | — | — | — | 27.8 | — | 25.2 |
| 25.3 | 48.0 | — | — | — | — | — | — | — |
| 25 | — | — | 48 | — | 47.6 | — | 46.0 | 36.7 |
| 24.6 | — | — | — | — | — | — | 48.0 | — |

*Corrections*

*a. Pressure exerted by rubber bulb.* The bulb was filled with air under known pressure and its volume measured by displacement.

The pressure exerted by the bulb varied from 1.1 cm. of mercury at 36 cc. volume to 2.2 cm. of mercury at 83 cc. volume (1.7 at 58 cc. and 2.1 at 69 cc.).

These pressures should be added to the pressure readings in all the preceding tables if absolute values are required. At present the work is solely of a comparative nature, hence this refinement has been omitted.

*b. Volume change due to rubber connecting tube and capillary manometer.* This was approximately 0.7 cc. for 48 cm. of mercury pressure rise. The value will be the same for conditioned or dry, hence a correction is unnecessary at present.

*c. Pressure exerted by water column in left leg of manometer.* At zero pressure in the jar *B* the right leg of the mercury manometer will register a slight pressure owing to the head of the water column over the mercury in the left leg. The manometer scale was therefore given a correction equivalent to this factor.

## Discussion of Results

*Asbestos*

*Pressure-volume relation.* The experimental results have been summarized in Table VIII and in the accompanying graphs. In Fig. 2 the compression and release cycles for dry asbestos fibre have been plotted. It is

TABLE VIII

AVERAGE VALUES FOR VOLUME AT DIFFERENT CYCLES AND RELATIVE HUMIDITIES

| Relative humidity, % | Initial vol., cc. 1st. cycle $V_a$ | Initial vol., cc. last cycle $V_b$ | Volume change in cc. between $p = o$ and $p = 48$ cm. Hg. | | $\frac{V_1}{V_a}$ | $\frac{V_2}{V_b}$ | Weight of samples, gm. |
|---|---|---|---|---|---|---|---|
| | | | 1st. cycle $V_1$ | Last cycle $V_2$ | | | |
| **Asbestos** | | | | | | | |
| 0.0 | 82.0 | 61.0 | 27.0 | 7.6 | .330 | .124 | 30.0 |
| 60.0 | 68.0 | 50.0 | 23.6 | 6.6 | .348 | .132 | 30.0 |
| 95.0 | 69.0 | 50.0 | 22.0 | 5.1 | .319 | .102 | 30.0 |
| **Cotton** | | | | | | | |
| 0.0 | 54.5 | 50.0 | 24.9 | 21.6 | .457 | .428 | 5.0 |
| 95.0 | 52.0 | 42.0 | 23.5 | 13.5 | .452 | .32[illegible] | 5.0 |
| **Wool** | | | | | | | |
| 0.0 | 56.0 | 54.0 | 30.9 | 29.7 | .552 | .550 | 3.5 |
| 95.0 | 54.0 | 47.0 | 28.7 | 22.4 | .530 | .478 | 5.0 |

apparent that the first compression results in a large amount of permanent deformation. The subsequent cycles continue the process but by the fifth cycle, the mass has nearly reached a position of equilibrium where the application and release of pressure will bring about repeatable volume changes. The ratio of volume change on the first and last cycles is seen in Table VIII (columns 6 and 7) (also Fig. 10).

It is of interest to note that the second compression curve falls well above the previous return, while a marked loop is formed owing to the fact that the return cycle shows very little volume change while pressure falls rapidly in the initial release. This indicates a "locked" condition after compression which prevents the volume from increasing until much lower pressures are reached. This state of affairs naturally follows when a deformation causes both bending of an elastic body and friction between this body and others.

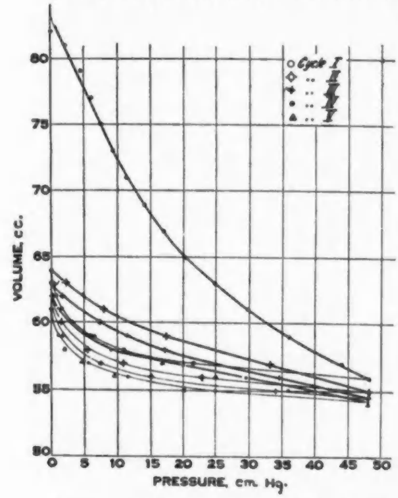


FIG. 2. *Pressure-volume relation of dry asbestos.*

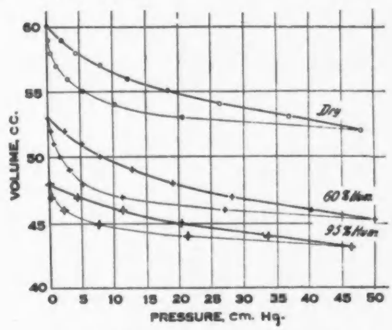


FIG. 3. *Effect of humidity on pressure-volume relation of asbestos fibre.*

A number of authors have obtained curves of this nature and have placed various interpretations on the areas.

Winson (5), investigating wool fibre, assumed that the loop areas in two cases, when volumes were plotted as percentage volume change, were a measure of the resiliency. This view is of course erroneous as it neglects the length of the loop and disregards the mechanical definition of resiliency.

Schiefer (3) in his work on compressibility of textile materials, regarded resiliency as the ratio of the work recovered from the fibre on the release stroke to the work done on the fibre on the compression stroke.

In the present work the stricter definition of resiliency will be adhered to. As mentioned previously, if the definition of resiliency be freed from the limitation of remaining within the elastic limit, the resiliency in this case is the work recovered as represented by the area under the release curves.

*Effect of sorbed water.* The aim of this research has been to demonstrate that sorbed water exerts a definite effect on the physical properties of asbestos

fibre. As a preliminary study three humidities have been chosen, *e.g.*, 0, 60, and 95%, corresponding to sorption values of 0.0 (dry at 104°C.), 1.3, and 3.0% respectively.

The effect of sorption is strikingly shown in the collected results in Table VIII and in Fig. 3, where the compression and return curves for the final cycles of typical experiments have been plotted. The most striking effect is the large change in apparent density which results from changes in sorption. Numerical values for this difference in density are given in Table IX.

It is to be noted that the ratio of densities is similar at zero pressure for any cycle, while the actual value is directly related to humidity and thus to sorption. These differences of apparent density must be of great importance in any measurement which depends on density, such as a screen test, hence this factor will have a direct bearing on the commercial testing of asbestos.

TABLE IX

VARIATION OF APPARENT DENSITY OF ASBESTOS FIBRE WITH HUMIDITY

| Relative humidity, % | Initial cycle | | 5th cycle | |
|---|---|---|---|---|
| | Density (apparent) | Ratio | Density | Ratio |
| 95 | .455 | 100 | .626 | 100 |
| 60 | .435 | 96 | .567 | 90 |
| Dry | .371 | 80 | .501 | 80 |

Very much higher pressures would be required to compress the dry fibres to the same volume as the conditioned fibres. At the same time the percentage reduction caused by a given pressure is remarkably similar in all cases, and appears to be independent of sorption.

*Resiliency.* By previous definition work recovered during the release stroke is the measure of the resilience. This has been measured in arbitrary units using the planimeter and the results appear in Table X.

TABLE X

ASBESTOS FIBRE—WORK DONE DURING $p\,v$ CYCLE ($p\,v$ IN ARBITRARY UNITS)

| Cycle No. | Dry fibre | | | | Fibre conditioned at 95% relative humidity | | | |
|---|---|---|---|---|---|---|---|---|
| | Compress. | Release | Diff. | Ratio | Compress. | Release | Diff. | Ratio |
| 1 | 2225 | 333 | 1992 | .15 | 2170 | 285 | 1885 | .13 |
| 2 | 759 | 300 | 459 | .40 | 653 | 264 | 389 | .40 |
| 5 | 601 | 245 | 356 | .40 | 423 | 230 | 173 | .53 |

*Cotton wool*

*Pressure-volume relation.* The pressure-volume curves for a typical sample of dry cotton wool are shown in Fig. 4. A curve very different from that for asbestos was obtained. The return curves fall much more closely on the compression curves and the difference between the first and subsequent cycles

is much less. The amount of locking of fibres is relatively less than with asbestos as the pressure does not fall nearly as rapidly on the release curves.

The dry samples are some 12% more resilient than those containing sorbed water, as will be seen by comparing the work done on release strokes. It is of interest to note that using Winson's definition (differences in Table X, a low value representing high resiliency) the dry fibre would be less resilient, but using Schiefer's (ratios in Table X) there would be no significant difference.

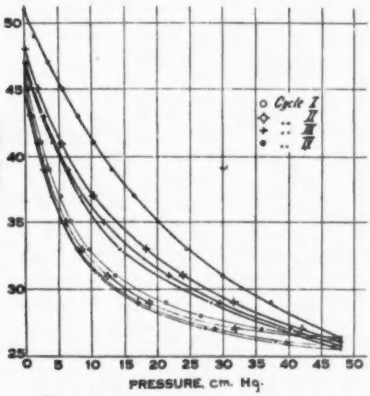


FIG. 4. *Pressure-volume relation of dry cotton wool.*

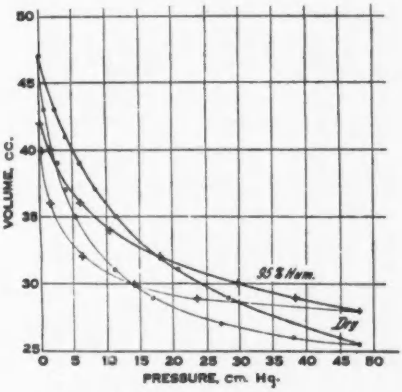


FIG. 5. *Effect of humidity on pressure-volume relation of cotton wool (final cycle).*

*Effect of water sorption.* In Fig. 5 are plotted the final cycles of cotton samples in the dry condition and in equilibrium with air at 95% humidity. In this condition, the cotton contains about 16% moisture, according to Urquhart (4). The curves may be best considered in conjunction with the values given in Table VIII.

There does not appear to be any difference in apparent density at the beginning of the initial stroke. This would be expected from the manner in which the cotton was packed in the rubber bulb. Considerable differences in behavior appear on compression, the conditioned sample being much less compressible, and though the loops are approximately the same size, the return loop for conditioned cotton shows an effect very similar to asbestos in which a small increase in volume entails a large drop in pressure, indicating a locked condition of the fibres (a sort of semi-permanent set).

The apparent density at the end of the compression stroke is reversed owing to the large compressibility of the dry fibre. Theoretical reasons will be advanced in a later part.

TABLE XI

COTTON FIBRE—WORK DONE DURING $p\ v$ CYCLE ($p\ v$ IN ARBITRARY UNITS)

| Compression loop | 4th cycle | |
|---|---|---|
| | Dry | 95% relative humidity |
| Compression stroke | 2116 | 1932 |
| Release stroke | 887 | 577 |

Values for resiliency appear in Table XI. The ratio of work done during release of the sample containing sorbed water to that of the dry fibre is lower than in the case of asbestos.

### *Wool*

While outside the scope of this research, wool is of general interest as it exhibits a very twisted fibre and one likely to show a very high degree of resilience.

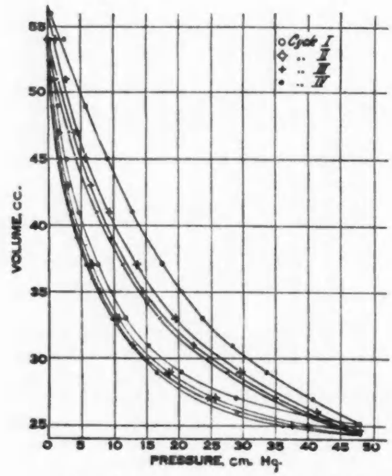


Fig. 6. *Pressure-volume relation of dry wool.*

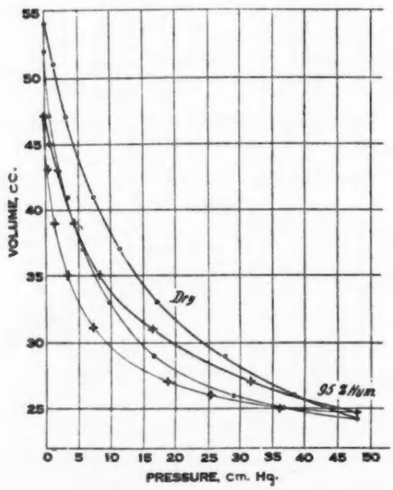


Fig. 7. *Effect of humidity on pressure-volume relation of wool (final cycle).*

*Pressure-volume relation.* The pressure-volume relation for dry wool fibre is shown in Fig. 6. It is at once apparent that much greater reversible volume changes are obtainable at the same pressure change than with cotton or asbestos. Practically no permanent set takes place (see also Fig. 10), the compression ratio on the first and final cycles being almost the same as shown in Table VIII.

*Effect of sorbed water.* The results of experiments on wool in the dry condition and containing sorbed water are shown in Fig. 7. The curves are not strictly comparable as the samples were not of the same weight. This discrepancy was unavoidable as the dry fibre occupied a much larger volume. However the effects of sorbed water are evident. The conditioned sample is less compressible and shows lower return and compression loops.

## Comparison of Asbestos, Wool, and Cotton

In Figs. 8 and 9, typical pressure-volume curves for the fibres under discussion have been plotted for both dry condition and in equilibrium with air at 95% humidity. The volume changes have been plotted as percentages of the volume at the beginning of the last cycle. It is apparent that though asbestos

may be compressed only from 10 to 15% of its volume, wool may be compressed some 55% of its original volume by the application of the same pressure. Cotton falls between the two, showing 45% for dry fibre and 33% for fibre containing sorbed water. The effect of sorption has been in each case to reduce the compressibility of the fibre mass.

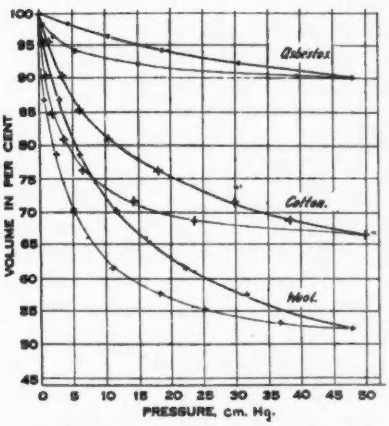


FIG. 8. *Pressure-volume relation of dry fibres (fourth cycle).*

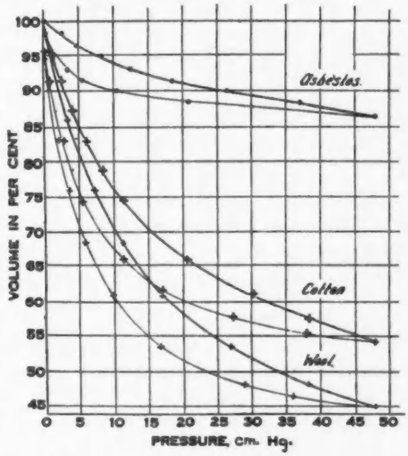


FIG. 9. *Pressure-volume relation of fibres at 95% relative humidity (fourth cycle).*

The pressure-volume curves have invariably been lowered by successive pressure and release cycles. This effect, which was greatest for asbestos and least for wool, is due to the fact that the fibres slip over one another to reach a position resulting in a smaller volume for the mass. The extent of this process is well shown in Fig. 10. In this graph, the pressure attained at a constant volume on succeeding cycles has been plotted against the appropriate cycle. As the fibres slip the pressure at any given volume falls with successive cycles. The differences between the fibres under discussion are at once apparent from this curve and the effect of sorbed water is very pronounced, particularly with asbestos and cotton. (Wool may not be directly compared owing to the weight discrepancy). Presumably one of the pronounced effects of sorbed water is to facilitate the slippage of the fibres.

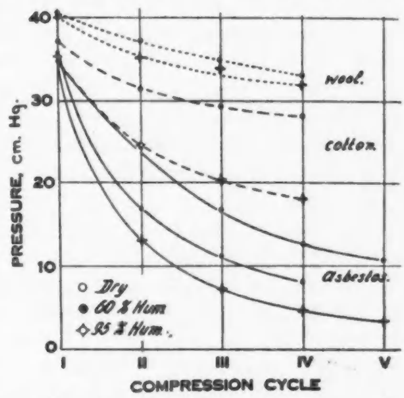


FIG. 10. *Effect of successive compression cycles on pressure (volume constant).*

It is, of course, apparent that the comparison between asbestos, cotton and wool may not be pressed very

closely because of the large differences in fibre length. When the length-volume relation is altered by shortening the fibre the resistance to bending is increased, which results in an increased tendency for slippage. This undoubtedly accounts for a part of the difference between asbestos and the other fibres which have been examined.

In general it seems that a definite measurable physical effect may be attributed to sorption by the organic and inorganic fibres examined. The effects may be summarized briefly as follows: (i) alteration of the shape of the compression and return loops; (ii) decrease in resilience; (iii) increase in apparent density; (iv) decrease in compressibility; (v) increase in the amount of permanent set or fibre slippage.

## Theoretical Discussion

*Asbestos*

It has been clearly shown that the amount of sorbed water affects the pressure-volume curves in a regular manner. As indicated previously, this change in property may be due to alteration in the structural or surface characteristics of the individual fibre units. The first result would naturally follow sorption in which the molecules of water penetrated into the molecular structure of the sorbing medium. The second result would follow a purely surface sorption. It is suggested here that the results may be explained by assuming that the surface altered so that slippage of the fibres was facilitated.

As mentioned before, these factors could be separated if experiments could be carried out on the effect of moisture on the individual unit, but as this is impossible in the case of asbestos, the two effects must be treated together. There is, however, some evidence that only one of the factors is operative in the present case.

In the first place, it seems unlikely that absorption, or penetration of water into the molecular structure takes place in asbestos. This would presumably be a slow process while the authors have shown previously that sorption of water by asbestos, up to a humidity of 65% at least, is fairly rapid when disturbing factors, such as the presence of air, are excluded. This absorption effect might be expected with organic fibres where chemically bound water may be removed at fairly low temperatures; with an inorganic compound like asbestos, on the other hand, rather high temperatures are required to remove this water so that it seems unlikely that absorption takes place at the temperatures existing in these experiments.

It seems more probable that it is the surface factor that is being affected in the present case. The enormous subdivision of which an asbestos fibre is capable shows that a very large surface may be presented. The experimental results will therefore be discussed on the assumption that the effect of sorbed water has been confined to the surface and that the structural characteristics of the ultimate fibre unit are not appreciably changed. The differences which have been noted may be explained on the assumption that the major effect of sorption is to increase the ease with which the fibres slip over one another.

It has been shown that the application of a given pressure will compress the fibre containing sorbed water to a higher apparent density than the dry fibre. On the assumption which has been made, the ready slippage of the fibres containing sorbed water enables them to collapse over one another until a position of "repose" is reached, after which the mass may not be compressed further unless higher pressures are applied. Dry fibres will not slip as readily over one another; therefore, they are forced to bend.

When a mass of fibre is subjected to a volume deformation a change in apparent density follows, caused by the operation of two major factors, deflection of the fibres and slippage. The extent of deflection will depend on the bending moment to which each fibre is subjected. For any given force this moment depends on the unsupported fibre length between contacts with neighboring fibres. As the apparent density increases, the number of contacts increases, and the moment for a given force decreases. Hence the individual fibres are less deflected by a given force and the fibre mass becomes less compressible and resiliency falls. A simple case of this is illustrated in Fig. 11, which shows five fibres in a fundamental position.

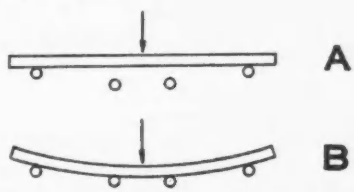

FIG. 11. *Effect of pressure on fibre deflection.*

In the initial stage *A* the fibre has insufficient strength to resist the stress; as it bends its resistance to deformation is increased by two factors, first, increased potential energy due to strain, and second, additional points of contact with adjacent fibres, which shorten the unsupported spans. This "stiffening" of the fibres means increased resistance to deformation, thus increasing the tendency for slippage. As this occurs more points of contact are formed and the compressibility of the mass falls, and apparent density increases. Therefore, it may be seen that if the average section modulus is unaltered, the pressure-volume relation of a mass of fibres is ultimately dependent on the ease with which they slip over one another.

If it is assumed that the effect of sorbed moisture is to facilitate this slippage, it follows that a mass of fibre in this condition will be more sensitive to compression, less resilient, and have a higher apparent density than a dry fibre.

In the above illustration, the simplest case of a horizontal beam has been chosen; actually of course, the reactions are enormously more complex, but the same general reasoning would apply.

This theoretical explanation appears to give a very satisfactory picture of compressional behavior of a mass of asbestos fibres. The shape of pressure-volume curve and the reason for apparent density differences which have been experimentally observed, are at once apparent. It has been noted that the resiliency of dry fibre is some 10% greater than for fibre containing sorbed water. This is predictable from theory, as the lower density and slip of the dry fibre allows a greater amount of volume change to take place by fibre bending. Hence, more work may be stored as potential energy.

*Rate of Slip*

Further evidence in favor of the explanation which has been offered is afforded by a measurement of the rate and amount of fibre slippage.

During the experiments it had been noticed that after a volume displacement some time elapsed before the pressure readings became constant. This is presumably due to slippage of the fibres resulting in a settling process. If the suggestions made above are valid, the process should be more rapid with fibre containing sorbed water. It was possible to measure the rate in the apparatus as employed. The pressure was rapidly increased at a constant rate to a fixed maximum, and pressure readings against time were then taken. The process was essentially that of measuring pressure change at a constant volume.

The first and second cycles of such a process appear in Fig. 12. It is at once apparent that both the rate and extent of slip are much greater for the fibre in equilibrium with air at 95% relative humidity. This appears to be very convincing evidence in favor of the theoretical explanation which has been put forward.

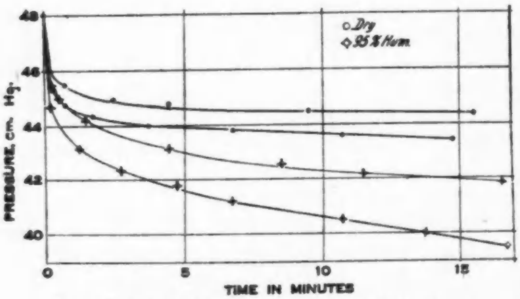


FIG. 12. *Effect of humidity on rate of fibre slippage.*

It might be suggested that the time required for the establishment of equilibrium was due to gas pressure in isolated pockets in the fibre mass. This is improbable as the time elapsed is sufficient for the entrained air to escape; furthermore, the order of magnitude of the observed effect would be reversed, as the rate of gas flow would be slowest through the fibre of highest apparent density.

*Practical Applications in the Case of Asbestos*

In the case of asbestos, the fibre bundle may be taken as the ultimate unit for practical purposes. The strength of this bundle of fibres will depend, among other factors, on the ease with which the individual fibres may slip over one another and as this is facilitated by the presence of sorbed water, a fibre bundle in this condition will be more flexible than such a bundle in the dry state.

This will have a direct bearing on the testing of asbestos. It is customary to screen the fibre through a number of standard meshes. It is obvious that at higher humidity, the long fibres will be more flexible and will pass through screens which would have held them, had they been dry. This fact has been noted in actual testing by one of the authors, but until now the reason has been in doubt. The difference in apparent density follows from the above and this will also exert a powerful effect on the screen test.

Only three humidities have been examined at present (0, 65 and 95%) so that the distribution of this effect over the range of sorption has yet to be elucidated. The sample at 60% relative humidity shows an initial apparent density similar to the samples at 95% relative humidity. Its behavior on compression is more like the dry fibre, while the loop falls half way between (see Fig. 3).

The properties which have been discussed must be greatly affected by fibre length but an examination of this factor involves a research in itself. It is possible that some relation between compressional behavior and fibre length might be obtained. Work of this nature is in projection.

*Extension of the Discussion to Organic Fibres*

That sorption affects the behavior of cotton and other organic fibres has long been known. The amounts of water which are taken up are much larger than those taken up by asbestos and the physical effects such as swelling, etc., are much more obvious. Hence, it would be expected that the physical properties of the individual fibres would be affected and perhaps also the surface characteristics as in the case of asbestos. Since a natural fibre unit of cotton is available it is possible to examine the surface and structural factors separately.

The first factor has been the subject of a number of researches. Clayton and Pierce (1) have shown that the elastic moduli of individual cotton hairs are influenced in a regular way by humidity. The resistance to both bending and torsion is reduced by sorbed water. It is therefore clear that the compressional behavior of a mass of cotton fibres will be affected by the alteration in section modulus caused by humidity.

It appears from the present results that the surface factor is also affected in such a manner as to increase the ease of slippage with increased amounts of sorbed water. While this effect is less marked than in the case of asbestos it is by no means negligible. This is seen in columns 6 and 7, Table VIII, where the average values for the ratio of volume change during compression to initial volume on the first and fifth cycles are 0.46 to 0.43 for the dry fibres and 0.45 to 0.32 for the conditioned fibres. Hence, considerably more packing has taken place in the latter case.

A combination of these two effects will readily explain the observed effects. In Fig. 4 it has been seen that while the apparent density of the dry fibre is lowest at the beginning of the compression it becomes greater than that of the conditioned fibre at the highest point of compression. This is probably connected with the swelling of the fibres on sorption of water. Clayton and Pierce (1) have shown that the volume of soda-boiled cotton is increased by some 12% by sorption of water from the dry condition to equilibrium with a humidity of 95%. Hence the swollen fibre may not be compressed as far as the dry fibre owing to this reduction in real density.

## References

1. Clayton, F. H. and Pierce, F. T. J. Textile Inst. 20 : T315-T332. 1929.
2. Pidgeon, L. M. and van Winsen, A. Can. J. Research, 9 : 153-158. 1933.
3. Schiefer, H. F. Bur. Standards J. Research, 10 : 705-713. 1933.
4. Urquhart, A. R. J. Textile Inst. 20 : T117-T124. 1929.
5. Winson, C. G. J. Textile Inst. 23 : T386-T393. 1932.

# THE ADSORPTION OF HYDROGEN SULPHIDE BY ACTIVATED ALUMINA[1]

By C. H. Bayley[2]

## Abstract

Measurements have been carried out on the adsorption of hydrogen sulphide on a commercial sample of "activated alumina" by the dynamic and static methods. The adsorption is influenced by prior heating of the alumina to various temperatures, being a maximum when the temperature of prior heating is 550° C.

The use of solid adsorbents for the removal of certain constituents of gaseous mixtures has received much attention in recent years. The use of silica gel in this connection is a familiar example. Aluminium hydroxide, when suitably treated, can be made to yield an oxide which possesses a high adsorptive capacity for many gases and vapors and a commercial grade of activated alumina suitable for such use has been on the market for some time.

The adsorption of a wide range of vapors by alumina has been investigated by Munro and Johnson (7). These authors emphasize the manner in which the adsorptive powers of the material are influenced by its water content. Boswell and Dilworth (1) have investigated the adsorption of ethylene on aluminium hydroxides containing known amounts of water, and have shown that there is, at a certain optimum water content, a maximum adsorption of ethylene. The use of "active" alumina as a desiccating agent has been investigated by Johnson (4) and others (2, 6).

The following are the results of an investigation upon the adsorption of hydrogen sulphide by one of the commercial grades of activated alumina. The extent of the adsorption of this gas from low partial pressure mixtures (0.5 to 2%) appeared to be of possible interest in connection with the purification of natural gas. Data were obtained regarding the extent of the adsorption of hydrogen sulphide from hydrogen sulphide-nitrogen mixtures and also in the absence of nitrogen by the static method. Owing to lack of time it was not possible to investigate the adsorption of hydrogen sulphide in admixture with the lower paraffin hydrocarbons. However, the results obtained are of interest, inasmuch as they reveal the existence of an optimum water content of the alumina which corresponds to maximum adsorptive activity.

## Experimental

### *Materials*

The hydrogen sulphide was obtained from a cylinder of the liquefied gas. Analysis by the usual iodine method showed it to have a purity of 99.6%. The sample of activated alumina was supplied by the Aluminium Corpor-

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*Contribution from the Division of Chemistry, National Research Laboratories, Ottawa, Canada.*
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ation of America through their Montreal office and was designated by them as Grade A. The sample was ground to 20-40 mesh.

*Apparatus*

In the stream experiments, which were of a preliminary nature, the alumina was located at the centre of a 10 by 200 mm. Pyrex tube which could be heated electrically; dry nitrogen containing definite percentages of hydrogen sulphide as obtained by Jacobson's modification (3) of the method of Dunkley and Leitch, was passed, at a measured rate, over the alumina, the exit gases passing over a small piece of filter paper moistened with lead acetate solution, and thence through two gas washers containing a measured volume of standard iodine solution. In order to avoid loss of iodine, a third gas washer containing 10% potassium iodide solution was connected to the end of the train. The hydrogen sulphide taken up by the alumina was expelled into the iodine solution by prolonged passage of nitrogen or by raising the temperature of the alumina, and hence a check was obtained upon the amount taken as calculated from the volume of nitrogen-hydrogen sulphide mixture passed through. At the end of the experiment the contents of the three tubes were mixed and titrated with thiosulphate.

In the experiments employing the static method, the usual type of apparatus was used. This consisted essentially of a manifold carrying a calibrated bulb, burette, adsorption chamber, mercury manometer and outlet tube through which the system could be evacuated. Connection between the adsorption chamber and the arm of the manifold was made through a mercury seal.

In order to determine the volume of the apparatus, the calibrated bulb was filled with dry air and closed off from the rest of the system. A weight of alumina equal to that to be used in the subsequent experiments was introduced into the adsorption chamber, which, along with the manifold and manometer arm, was evacuated. The level of the mercury in the manometer was brought to the zero of the scale, and the pressure read. By opening the tap to the calibrated bulb and again reading the pressure, the volume of the adsorption system could be calculated. This method neglects any error arising from the adsorption of oxygen or nitrogen by the alumina, but this has been shown to be small. Pressures were read to the nearest millimetre of mercury and volumes to 0.1 cc. The temperature of the adsorption vessel was not regulated, being 22° ± 2° C. In the data, all gas volumes are corrected to 0° C. and 760 mm.

*(a) Stream Experiments*

Experiments were run with nitrogen-hydrogen sulphide mixtures of various compositions, the passage of the mixture being discontinued as soon as the lead acetate paper showed blackening. The hydrogen sulphide remaining in the reaction tube, as well as that adsorbed by the alumina, was then swept into the iodine with a current of nitrogen. In calculating the amount of hydrogen sulphide adsorbed, allowance was made for the amount of gas

remaining in the reaction tube. It was found that only a portion of the adsorbed gas was removed by nitrogen even after the latter gas was passed through for several hours. Upon raising the temperature of the alumina to 200° C., most of the hydrogen sulphide could be quantitatively recovered, but the amount recovered was always less than the amount used. This would indicate that a portion of the hydrogen sulphide had reacted chemically with the alumina. During the process, a small amount of moisture was formed and upon repeating the passage of the nitrogen-hydrogen sulphide mixture it was found that the extent of the adsorption, for a given partial pressure of hydrogen sulphide, had increased. The alumina was heated to 200° and 400° C. in a current of dry nitrogen and the adsorption measured after each heating. The results are shown in Table I.

TABLE I

ADSORPTION OF HYDROGEN SULPHIDE BY ACTIVATED ALUMINA, GRADE A. STREAM EXPERIMENTS

| Weight of alumina, gm. | Rate of passage of gas mixture, cc./min. | Partial pressure $H_2S$, mm. | Temp. to which alumina was heated in $N_2$, °C. | $H_2S$ adsorbed per gm. alumina, cc. |
|---|---|---|---|---|
| 4.0000 | 10 | 224.0 | Not heated | 3.9 |
| 4.0000 | 10 | 52.5 | 200 | 5.4 |
| 4.0000 | 10 | 58.0 | 200 | 5.5 |
| 4.0000 | 10 | 67.1 | 400 | 6.1 |

### (*b*) *Static Experiments*

Curve 1, Fig. 1, shows the results obtained with a sample of the alumina that had not received heat treatment. The desorption curve lies only slightly above that for the adsorption. The extent of the adsorption is relatively small, corresponding to 7.6 cc. per gram of material at a partial pressure of 714 mm.

Curve 2, Fig. 1, represents the adsorption on a similar sample which had been heated to 700° C. for two hours in a current of nitrogen, during which considerable quantities of water were evolved. The amount of adsorption is very much greater, being 20.5 cc. per gram of material at a partial pressure of 790 mm. In this case there was a well marked hysteresis of desorption

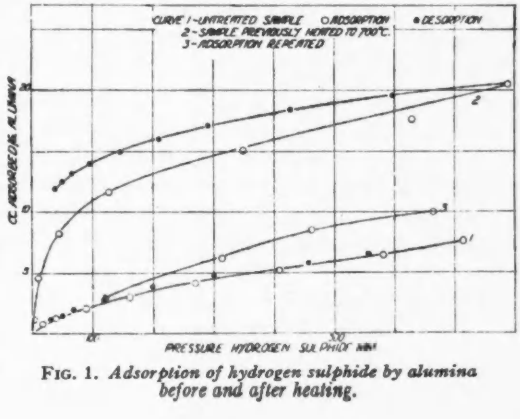


FIG. 1. *Adsorption of hydrogen sulphide by alumina before and after heating.*

and on lowering the pressure to 10 mm. there was still an unrecovered amount of hydrogen sulphide equal to 10 cc. per gram remaining on the alumina.

Curve 3, Fig. 1, shows the results obtained upon repeating the adsorption on the desorbed sample. The curve is similar in shape to Curve 2 but the extent of the adsorption is less than that shown in the latter by an amount approximately equal to the amount of gas that was not previously desorbed. Upon heating to 200° C. in a current of nitrogen, all of the gas held by the alumina was evolved and upon repeating the adsorption, the curve obtained coincided with Curve 2.

This observation, which was also made in the stream experiments, suggests that a portion of the hydrogen sulphide which is taken up reacts chemically with the alumina to form a compound which decomposes to liberate the gas on heating to 200° C. A yellow coloration developed on the alumina in these experiments. Its nature was not investigated.

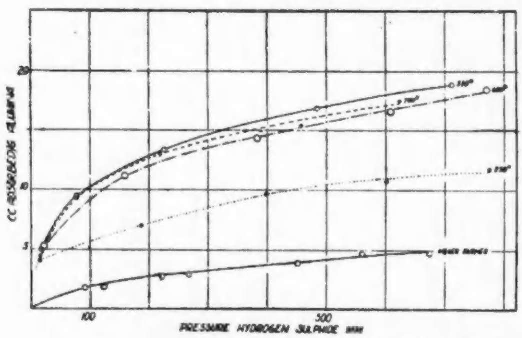

FIG. 2. *Adsorption of hydrogen sulphide by alumina heated to various temperatures.*

Fig. 2 shows the results obtained in a series of experiments in which 5-gm. samples of the alumina were heated respectively to 250°, 400°, 550°, 700°C. and strongly ignited with a Meker burner. The time of heating was three hours in every case.

For a given partial pressure, the extent of the adsorption steadily increases and reaches a maximum in the case of the sample heated to 550° C. In the strongly ignited sample, the extent of the adsorption has fallen to a value below that given by the unheated sample. This is undoubtedly due to the effect of sintering of the surface. It is probable that this effect would be noticed in a sample which had been subjected to prolonged heat treatment at 550° C. However, this appears to be the most suitable temperature to employ in the activation process provided the heating is not prolonged.

The water evolved in the various heat treatments was determined in each case. Table II shows the relation between the amount of water remaining on the alumina and the extent of the adsorption at three partial pressures. The total amount of water on the material was determined by measuring the loss in weight of a similar sample when heated to 1000° C. in an electric muffle, to constant weight. The optimum water content for maximum adsorption appears to be between 1.4 and 1.1% based on the original weight of the material prior to dehydration.

It will be observed that, for a given partial pressure of hydrogen sulphide, the adsorption values obtained in the stream experiments are lower than in the static experiments. This is due to the fact that in the former experiments

TABLE II

EFFECT OF WATER CONTENT ON ADSORPTION OF HYDROGEN SULPHIDE BY ACTIVATED ALUMINA, GRADE A

| Material | Initial water/gm. | Temp. of heating in N, °C. | Water off, gm. | Residual water, gm. | Adsorption, cc. per gm. | | |
|---|---|---|---|---|---|---|---|
| | | | | | 50 mm. | 100 mm. | 400 mm. |
| Grade A | 0.1035 | 400 | 0.0424 | 0.0611 | 7.4 | 12.0 | 14.6 |
| Grade A | 0.1035 | 550 | 0.0891 | 0.0144 | 8.4 | 13.0 | 15.7 |
| Grade A | 0.1035 | 700 | 0.0923 | 0.0112 | 8.4 | 13.0 | 15.3 |
| Grade A | 0.1035 | 280 | 0.0332 | 0.0703 | 5.5 | 6.7 | 10.2 |
| Grade A | 0.1035 | Not heated | — | 0.1035 | 1.5 | 3.5 | 5.0 |
| Grade A | 0.1035 | 1000 | 0.1035 | — | 1.2 | 1.8 | 3.8 |

the treatment was stopped as soon as hydrogen sulphide appeared in the exit gas and hence equilibrium between the gas and adsorbent was not reached.

The observation that silica gel and alumina which possess certain definite contents of water exhibit a maximum adsorptive power for various gases and vapors has been made by McGavack and Patrick (5), Munro and Johnson (7), and Boswell and Dilworth (1). These papers carry a full discussion of this phenomenon.

It should be noted that the value for the optimum water content of the activated alumina here investigated is considerably lower than that found by Munro and Johnson for the maximum adsorption of water vapor and by Boswell and Dilworth for that of ethylene. This is probably due to the fact that the activated alumina used here unquestionably possessed a smaller extent of active surface per gram than did that of the finely divided aluminium hydroxides used by the above investigators.

## Acknowledgment

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## References

1. BOSWELL, M. C. and DILWORTH, H. M. J. Phys. Chem. 29 : 1489-1505. 1925.
2. DOVER, M. V. and MARDEN, J. W. J. Am. Chem. Soc. 39 : 1609-1614. 1917.
3. JACOBSON, D. L. Am. Gas Assoc. Monthly, 8 : 459-461. 1926.
4. JOHNSON, F. M. G. J. Am. Chem. Soc. 34 : 911-912. 1912.
5. MCGAVACK, J. and PATRICK, W. A. J. Am. Chem. Soc. 42 : 946-978. 1920.
6. MARDEN, J. W. and ELLIOTT, V. Ind. Eng. Chem. 7 : 320-321. 1915.
7. MUNRO, L. A. and JOHNSON, F. M. G. Ind. Eng. Chem. 17 : 88-92. 1925.

# INVESTIGATION OF VARIOUS PHYSICO-CHEMICAL FACTORS WHICH INFLUENCE SULPHITE COOKING[1]

BY H. H. SAUNDERSON[2] AND O. MAASS[3]

## Abstract

The penetration of aqueous sulphite solutions into differently shaped blocks of spruce wood has been investigated, the effect of the shape and type of wood, and of the presence of imprisoned air being determined. Measurements of the rates of diffusion of the constituents of calcium bisulphite solutions into pre-soaked blocks of wood showed that "free" sulphur dioxide diffused more readily than calcium bisulphite. Adsorption of sulphur dioxide and calcium bisulphite solutions by spruce wood was measured at 30° and 50° C., and the influence of this factor on penetration was determined. The effect of penetration on delignification indicated the necessity of a satisfactory distribution of the lime salt at a low temperature to avoid localization of the lime during the pulping process.

## Penetration

In a previous paper (9), the authors discussed the forced penetration of aqueous sulphite solutions into spruce wood, due to a difference in the hydrostatic pressure of the liquid on two sides of the piece of wood. The present paper reports an investigation on the penetration of aqueous sulphite solutions into wood blocks of various shapes where the solutions completely surround the wood. This approaches more closely to the conditions in the sulphite process of manufacturing wood pulp, and the results obtained may be applied to explain some of the features of that process.

Edwardes (1) found that with disks $\frac{5}{8}$, 1 and 2 in. in thickness, the penetration of liquid depended more on the pressure applied than upon any preliminary evacuation of the wood, a result contrary to that reported by Enge (2). Schwalbe and Berndt (10) compared the absorptions from equimolar solutions of calcium and magnesium bisulphites by blocks of wood averaging 40 by 7 by 2 mm. They found that the calcium and magnesium salts were removed to about the same extent, the amount of absorption being measured by weighing the soaked blocks. Schwalbe and Lange (11) found that heartwood and sapwood of spruce could be differentiated by their relative absorptions from magnesium bisulphite solutions. They found also that free sulphur dioxide solutions were absorbed more readily than those in which the sulphite was in the form of the magnesium salt. Richter (7) placed commercial spruce chips in bottles, added a definite volume of sulphite liquor, then observed the change in concentration with time.

In these various results, no attempt was made to separate diffusion from adsorption or chemical absorption. Such adsorption would be very important with regard to the penetration of sulphite liquor, but very little work has been done on the adsorption of either calcium bisulphite or sulphur dioxide

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by wood. Grace (3) studied the sorption of gaseous sulphur dioxide on small blocks of wood, and found that the amount of gas held increased continuously for 10 hr., the maximum being 13.6%. Of this amount, about 4% could not be removed by evacuation for 24 hr.

Natural penetration was studied in two ways, each of which would yield certain information. Sinkage tests were performed on various types and shapes of wood blocks under varying conditions. Richardson (6) found that practically a constant percentage absorption of solution was required to cause a block to sink, so the time a block took to sink was a measure of the rate of penetration of the liquor into it. The other method of approach was to study the concentration changes of sulphite liquor surrounding pre-soaked blocks of wood of various shapes. This gave an indication of the rate of diffusion of the solute particles into the wood. In order to estimate the effect of adsorption, some measurements were made of the amount of free and combined sulphur dioxide which could be adsorbed by wood. The effect on the pulp of the failure of the constituents of the liquor to penetrate satisfactorily was also tested in order to apply the penetration data to the problem of commercial sulphite "cooking."

## Procedure

### *Sinkage Tests*

Richardson's method for measuring the rate of penetration of liquids into various shapes of wood blocks was employed. Ten standard shapes of blocks were used, each being 2 gm. in weight. The measurements of the 10, measured longitudinally along the fibre direction were 2.5, 5, 7, 9.8, 15, 19, 32, 52, 90, and 128 mm. The transverse sections were square, of sufficient area to give a two-gram block. The apparatus used was a large vacuum desiccator, having an inlet tube through which liquid could be admitted quickly. A removable brass screen was arranged to fit about 2 in. from the bottom of the desiccator.

The samples of wood were placed on the bottom of the desiccator, then the screen fitted over them. The desiccator was evacuated for 15 min. using a water vacuum pump which reduced the pressure to about 10 mm. of mercury. Then sulphite liquor of the desired strength was allowed to run into the desiccator rapidly until it had filled all the region below the screen. Atmospheric pressure was restored, and the time it took the blocks to sink was noted.

### *Diffusion Tests*

Blocks of wood of various shapes, previously soaked in water, were placed in sulphite solution, and the change in concentration of the sulphite liquor around the blocks gave a measure of its penetration into the wood. In addition to this simple diffusion, two other factors affected the sulphite concentration. The water in the soaked wood diffused outward into the solution, diluting it, and the wood surface acted as an adsorbent for both the free and combined sulphur dioxide.

The wood used was prepared in a manner similar to that used in the sinkage tests. Twenty blocks of approximately one gram each were made for each run, all blocks being of the same length, measured along the fibre. The weight of the 20 blocks was taken as a group. A sample of the same wood was used for a moisture determination, and from this the ovendry weight of the blocks was calculated. The blocks were carefully soaked in water by alternate evacuation and pressure for several days, by which time they were well filled. They were then rolled over blotting paper to remove surface moisture, allowed to stand in the air for 15 min., and weighed. Knowing the calculated ovendry weight and the weight of the wood when soaked, the amount of water introduced with the wood was determined.

The blocks were placed in a 125-cc. glass-stoppered reagent bottle filled with a measured amount of sulphite liquor of known strength. At intervals analyses were made of samples withdrawn from the bottle. The error introduced by the removal of this liquid was small, and no correction was made for it.

*Adsorption Tests*

The side arm of a 200-cc. Pyrex distillation flask was bent up parallel to the neck. A straight glass tube fitted through a rubber stopper down into the centre of the flask. This apparatus was connected to the original penetration apparatus (9, p. 418) by a heavy rubber tubing, clamped on. The feed tube from the penetration apparatus was connected to the side arm, the central glass tube leading to the outlet valve. The flask was fitted into the oil bath for temperature control.

The flask was filled with ovendry spruce flakes, then the central glass tube was worked down until the end of it was near the centre of the flask, and the rubber stopper was wired in place. The flask and wood were evacuated to a pressure of about 5 mm. of mercury, using a Hyvac pump connected to the outlet tube. Then the solution was allowed to flow into the evacuated flask. For the next 15 min. a gentle stirring motion was given to it by hand. At the end of 15 min., the outlet tube was flushed with about 15 cc. of liquid, and a test sample was withdrawn and analyzed.

Comparison of Runs 61 and 62 indicates that the dry heartwood sank much more quickly than the fresh-cut wood. This difference was due probably to a greater ease of removal of air in the evacuation of the dry wood.

The difference caused by evacuation of the sapwood was shown in Runs 63 and 64. In Run 64, in which the air was not removed, the time of sinking was several thousand times greater than that of the corresponding evacuated blocks. The relative order of sinking shows a slight change also. Where there was evacuation, the block that sank the most slowly was longer in proportion to its weight than the block from which the air had not been removed. Evidently the imprisoned air can diffuse out laterally, but the chief inflow of liquid into evacuated wood is along the tracheids.

## TABLE I

### Results of sinkage tests

| $SO_2$ conc. in soln., % | Preliminary treatment | Length of block, mm. | Approx. cross section of block, sq. mm. | Time to sink | Length of block, mm. | Approx. cross section of block, sq. mm. | Time to sink |
|---|---|---|---|---|---|---|---|
| **Run No. 61—Fresh heartwood. Temp., 25° C.** | | | | | | | |
| Total, 4.99 | Evacuation | 2.5 | 1900 | 25 sec. | 19.0 | 250 | 4 days* |
| Free, 3.74 | to 10 mm. | 5.0 | 950 | 14.5 min. | 32.0 | 150 | 6 days |
| Comb'd., 1.25 | press. for 15 min. | 7.0 | 650 | 69 min. | 52.0 | 90 | 15 days |
| | | 9.8 | 480 | 5.5 hr. | 90.0 | 52 | 16 days |
| | | 15.0 | 320 | 16.0 hr. | 128.0 | 37 | 16 days |
| **Run No. 62—Air-dry heartwood.* Temp., 25° C.** | | | | | | | |
| Total, 4.99 | Evacuation | 2.5 | 2200 | 30 sec. | 19.0 | 290 | 65.0 min. |
| Free, 3.74 | to 10 mm. | 5.0 | 1100 | 1.5 min. | 32.0 | 170 | 44.5 min. |
| Comb'd., 1.25 | press. for 15 min. | 7.0 | 790 | 18.0 min. | 52.0 | 105 | 6 hr. |
| | | 9.8 | 560 | 32.0 min. | 90.0 | 61 | 11 hr. |
| | | 15.0 | 370 | 28.0 min. | | | |
| **Run. No. 63—Fresh sapwood. Temp., 25° C.** | | | | | | | |
| Total, 5.12 | Evacuation | 2.5 | 1500 | 20 sec. | 18.8 | 200 | 75 sec. |
| Free, 3.84 | to 10 mm. | 5.0 | 750 | 20 sec. | 32.0 | 115 | 270 sec. |
| Comb'd., 1.28 | press. for 15 min. | 7.1 | 535 | 20 sec. | 51.0 | 75 | 345 sec. |
| | | 10.0 | 380 | 20 sec. | 90.0 | 42 | 650 sec. |
| | | 15.0 | 250 | 35 sec. | 128.0 | 30 | 405 sec. |
| **Run No. 64—Fresh sapwood. Temp., 25° C.** | | | | | | | |
| Total, 5.12 | No | 2.5 | 1500 | 9 hr. | 18.8 | 200 | 16 days |
| Free, 3.84 | preliminary | 5.0 | 750 | 3 days | 32.0 | 115 | 24 days |
| Comb'd., 1.28 | evacuation | 7.1 | 535 | 3.5 days | 51.0 | 75 | 23 days |
| | | 10.0 | 380 | 4 days | 90.0 | 42 | 18 days |
| | | 15.0 | 250 | 14 days | 128.0 | 30 | 10 days |
| **Run No. 65—Fresh heartwood. Temp., 50° C.** | | | | | | | |
| | | Length of block, mm. | | Time to sink | Length of block, mm. | | Time to sink |
| Total, 5.00 | Evacuation | 2.5 | | 30 sec. | 19.0 | | 9 days† |
| Free, 3.80 | for 15 min. | 5.0 | | 15 hr. | 32.0 | | 10 days |
| Comb'd., 1.20 | | 7.0 | | 2 days | 52.0 | | 8 days† |
| | | 9.8 | | 4 days | 90.0 | | 12 days |
| | | 15.0 | | 7 days† | 128.0 | | 11 days |

**This wood was not from the same sample as the wood used in Run No. 61, but had about the same number of rings per inch, and appeared to be of the same structure.*

*†At the end of five days the temperature was lowered to 25° C. The samples noted all dropped to the bottom, but when the temperature of 50° C. was restored, they rose again.*

TABLE II

RESULTS OF DIFFUSION TESTS

| Wood | Vol. of sol. added, cc. | Conc. of sol. added, % | Equilibrium conc.* of sol., % | Time in min. | Conc. of the sol. around the wood: Free, $SO_2$, % | Conc. of the sol. around the wood: Combined $SO_2$, % |
|---|---|---|---|---|---|---|
| **Run No. 71** | | | | | | |
| Type—fresh heartwood | 75.5 | Free $SO_2$, 3.33 | Free $SO_2$, 2.36 | 5 | 2.72 | 1.22 |
| Length, along fibres, 5 mm. | | Comb'd. $SO_2$, 1.20 | Comb'd. $SO_2$, 0.85 | 20 | 2.50 | 0.95 |
| Oven-dry wt., 17.46 gm. (calcd.) | | | | 50 | 2.15 | 0.97 |
| | | | | 110 | 2.02 | 0.90 |
| Wt. after soaking, 48.36 gm. | | | | 235 | 1.99 | 0.89 |
| | | | | 470 | 1.97 | 0.85 |
| Wt. of water in wood, 30.90 gm. | | | | 1435 | 1.94 | 0.81 |
| **Run No. 72. Temp., 25° C.** | | | | | | |
| Type—fresh heartwood | 81.6 | Free $SO_2$, 3.35 | Free $SO_2$, 2.46 | 5 | 3.07 | 1.13 |
| Length, along fibres, 10 mm. | | Comb'd. $SO_2$, 1.16 | Comb'd. $SO_2$, 0.85 | 20 | 2.81 | 1.04 |
| | | | | 50 | 2.59 | 1.05 |
| Oven-dry wt., 16.43 gm. (calcd.) | | | | 120 | 2.37 | 0.89 |
| | | | | 240 | 2.13 | 0.93 |
| Wt. after soaking, 46.02 gm. | | | | 480 | 2.10 | 0.83 |
| | | | | 1500 | 2.07 | 0.78 |
| Wt. of water in wood, 29.59 gm. | | | | 6000 | 2.01 | 0.72 |
| **Run No. 73. Temp., 25° C.** | | | | | | |
| Type—fresh heartwood | 82.0 | Free $SO_2$, 3.35 | Free $SO_2$, 2.40 | 15 | 3.01 | 1.05 |
| Length, along fibres, 19 mm. | | Comb'd. $SO_2$, 1.16 | Comb'd., 0.83 | 60 | 2.70 | 1.06 |
| | | | | 120 | 2.53 | 1.00 |
| Oven-dry wt., 16.05 gm. (calcd.) | | | | 240 | 2.32 | 0.93 |
| | | | | 480 | 2.14 | 0.93 |
| Wt. after soaking, 48.26 gm. | | | | 1500 | 2.03 | 0.81 |
| | | | | 6000 | 1.95 | 0.75 |
| Wt. of water in wood, 32.21 gm. | | | | | | |
| **Run No. 74. Temp., 25° C.** | | | | | | |
| Type—fresh heartwood | 87.0 | Free $SO_2$, 3.33 | Free $SO_2$, 2.48 | 30 | 2.86 | 1.22 |
| Length, along fibres, 32 mm. | | Comb'd. $SO_2$, 1.18 | Comb'd. $SO_2$, 0.88 | 90 | 2.68 | 1.10 |
| | | | | 210 | 2.45 | 1.12 |
| Oven-dry wt., 15.59 gm. (calcd.) | | | | 435 | 2.31 | 1.07 |
| | | | | 1215 | 2.21 | 0.92 |
| Wt. after soaking, 45.24 gm. | | | | 1905 | 2.14 | 0.87 |
| | | | | 2625 | 2.01 | 0.84 |
| Wt. of water in soaked wood, 29.65 gm. | | | | | | |
| **Run No. 75. Temp., 25° C.** | | | | | | |
| Type—fresh heartwood | 76.0 | Free $SO_2$, 3.35 | Free $SO_2$, 2.45 | 30 | 2.82 | 1.07 |
| Length, along fibres, 65 mm. | | Comb'd. $SO_2$, 1.16 | Comb'd., 0.85 | 90 | 2.62 | 1.04 |
| | | | | 240 | 2.34 | 1.00 |
| Oven-dry wt., 18.49 gm. (calcd.) | | | | 480 | 2.18 | 0.95 |
| | | | | 1500 | 2.10 | 0.87 |
| Wt. after soaking, 46.37 gm. | | | | 6000 | 2.02 | 0.78 |
| Wt. of water in soaked wood, 27.88 gm. | | | | | | |

**Assuming that there is no adsorption or chemical action which will remove sulphite from the solution.*

In heartwood, the least effective shape for absorption seems to be approximately 100 mm. long by 7 mm. by 7 mm. for a two-gram block when the wood is evacuated. To reach the centre, liquid from the ends would travel 50 mm. as compared to 3.5 mm. from the sides, which gives an indication of the relative velocities. No data were recorded for sinkage tests on heartwood where no evacuation was used.

The effect of a rise in temperature on the rate of sinking is rather remarkable. It is well known that diffusion is much greater at higher temperatures, so the increased time of sinking at 50° C. must be due to some other factor. The answer probably lies in the interesting test performed after Run 65 had been in progress for five days, when the solution was cooled to 25° C. The fact that three more blocks sank, and then rose again as the temperature was restored to 50° C. indicates that air pockets in the wood were keeping the solution out. The contraction of the gas as the temperature dropped sufficed to let the block absorb enough liquid to sink.

From these results, it is evident that the flow of liquids is much greater in a direction along the fibres than across them, but diffusion will take place across them.

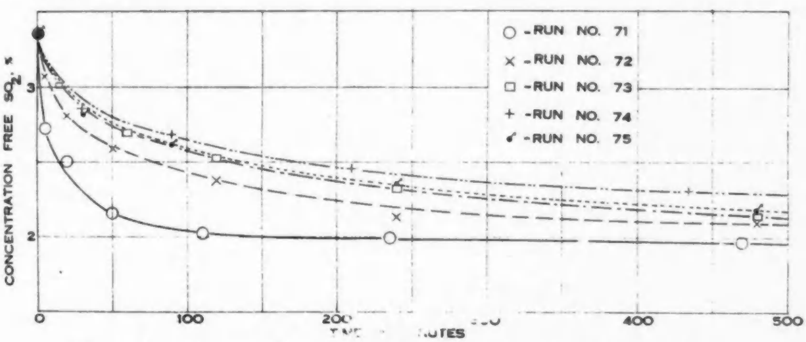


FIG. 1. *Rate of [illegible] of free sulphur dioxide for chips of different shapes.*

The results for the change in concentration of free sulphur dioxide in Runs 71 to 75 are shown graphically in Fig. 1.

In all the runs, the decrease in free sulphur dioxide was much more rapid than that of the combined. This may have been due to two causes; the free sulphite may diffuse more rapidly into the wood, or it may be adsorbed to a greater extent. The amount of adsorption is too small (see below) to account for all the change, so the free sulphur dioxide must diffuse more rapidly than the combined form. It is very probable that both factors contribute to the rapidity of the decrease.

The decrease of both free and combined sulphur dioxide in each run to a value below the calculated equilibrium was expected, owing to the known adsorption of sulphite on wood. The fact that free sulphur dioxide is adsorbed to a greater extent accounts for the greater drop below the equilibrium value.

A comparison of the five runs indicates the shape of block which removes the solute most slowly. For one-gram chips, this is the 32 mm. block, which apparently is the least effective shape to permit penetration by diffusion. It is noticeable that while this wood does not remove the sulphite rapidly, it continues to do so gradually over a long time period. The decrease in combined sulphur dioxide is proportionately not so rapid as that of the free in the early stages of a run, but toward the end of the run, its decrease is proportionately greater.

TABLE III

ADSORPTION TESTS

| — | Run No. 46 | Run No. 47 | Run No. 48 | Run No. 49 |
|---|---|---|---|---|
| Temperature, °C. | 30 | 30 | 50 | 50 |
| Pressure, atm. | 2 | 2 | 2 | 2 |
| Weight of oven-dry wood, gm. | 45.96 | 43.46 | 45.47 | 44.60 |
| Volume of solution added, cc. | 171 | 171 | 171 | 171 |
| Concentration of solution added | | | | |
| Free $SO_2$, % | 1.98 | 1.94 | 1.97 | 1.84 |
| Combined $SO_2$, % | 1.38 | 1.39 | 1.38 | 1.41 |
| Analysis of solution after 15 min. | | | | |
| Free $SO_2$, % | 1.87 | 1.82 | 1.90 | 1.79 |
| Combined $SO_2$, % | 1.35 | 1.37 | 1.36 | 1.39 |
| Weight of free $SO_2$ adsorbed per gm. of wood, gm. | 0.0041 | 0.0048 | 0.0026 | 0.001 |
| Weight of combined $SO_2$ adsorbed per gm. of wood, gm. | 0.0011 | 0.0008 | 0.00075 | 0.00[illegible] |

In general, the adsorption of free sulphur dioxide is about four times as great as that of combined sulphur dioxide. In both the temperature coefficient is negative, as would be expected for true adsorption, but the decrease is more marked with the free than with the combined sulphur dioxide.

## The Relation of Penetration to Delignification

The practical effect of a lack of satisfactory penetration was investigated. In this work, the extent of delignification of the wood was accepted as an index of satisfactory cooking conditions. Four groups of experiments were arranged as follows:—*(a)* The effect of the forced penetration of ordinary sulphite solution through wood during the course of an ordinary "cook." *(b)* The effect of a rapid rise in temperature in the early stages of a "cook" on penetration and delignification. *(c)* The influence of penetration on the effect of cooking with sulphur dioxide solutions only. *(d)* The influence of penetration on the effect of cooking with lime solutions only.

*The Effect of Forced Penetration*

Three disks of air-dry heartwood, 2 cm. in thickness and 3 cm. in diameter, were made from one block of wood. The first of these was fitted into the apparatus for forced penetration (9) and was completely filled with sulphite liquor at room temperature. This disk was cooked for seven hours, the temperature rising to 110° C. in two hours, then gradually to 140° C. at the end of seven hours, a flow of about 3 cc. of liquor every 10 min. being maintained through the wood. At the end of seven hours, the wood was cooled rapidly, washed out with cold water, dried, and analyzed for lignin according to the method of Ross and Potter (8). The second block was filled with sulphite liquor by forced penetration at low temperature. It was then placed in the forced penetration apparatus and cooked loose, about 3 cc. of liquor being removed from around it every 10 min. The same range and duration of temperatures were used. The block was then analyzed. The third block was treated as the second, except that the preliminary filling was with water instead of sulphite liquor, the block then being cooked in sulphite liquor. Results are shown in Table IV.

TABLE IV

EFFECT OF FORCED PENETRATION ON DELIGNIFICATION

| — | No. 51 Continuous penetration | No. 52 Preliminary sulphite penetration | No. 53 Preliminary water penetration |
|---|---|---|---|
| Lignin in product, % | 13.13 | 17.41 | 22.95 |

NOTE.—*Concentration of solution: free $SO_2$, 1.89%; combined $SO_2$, 1.22%; pressure, 7 atm.*

Comparison of the three runs shows the effect of a supply of cooking liquor. Where there was a continuous fresh supply due to forced penetration, the delignification was more rapid, although in Run 52 the preliminary penetration of sulphite liquor assured the presence of the necessary reagents. The removal of reaction products in Run 51 probably contributed to the rate of delignification also. In Run 53, where the sulphite liquor had to diffuse into the wood, there was a much slower reaction. This established definitely the importance of satisfactory penetration.

*The Effect of a Rapid Rise in Temperature*

Two blocks of air-dry heartwood, 2 cm. in thickness and 3 cm. in diameter, were made from the same block of wood used in Runs 51 to 53. One of these was filled by preliminary penetration with a sulphite liquor which contained enough lime and sulphur dioxide to cook the wood, the amounts being calculated from Klason's figures (5). The other block was filled with water. The

TABLE V

EFFECT OF A RAPID RISE IN TEMPERATURE ON DELIGNIFICATION

| — | No. 54 Preliminary sulphite penetration | No. 55 Preliminary water penetration |
|---|---|---|
| Lignin in product, % | 11.73 | 31.26 |

NOTE.—*Concentration of solution: free $SO_2$, 2.87%; combined $SO_2$, 2.09%. Pressure, 7 atm.*

blocks were cooked loose in the usual type of penetration apparatus (9). The cell was filled with sulphite liquor, the temperatures raised to 140° C. in 18 min., and maintained for five hours. No fresh liquor was introduced during the run.

The apparently increased amount of lignin over that in the original wood is due to the decreased amount of cellulose and other constituents, which leaves a larger relative amount of lignin.

At the end of the cook in Run 54, the wood was lighter in color than normal wood, and was easily broken apart into fibres. The product of Run 55 was quite hard, and was brown in the centre. Along the ends of the block, the wood was of the same light color observed in the former run. This was evidently the only part delignified, while the centre was slightly burnt. Under the conditions of cooking used, the precipitation of a lime salt on the surface of the block probably let only a small amount of lime into the wood. This prevented the formation of calcium salts of the lignosulphonic acids, and the removal of the lignin in that form.

Run 54 showed that a rapid increase in temperature did not cause burning, provided that a sufficient supply of lime and sulphur dioxide was present. The slow temperature rise necessary in the usual mill cooks was thus proved to be due to lack of penetration rather than to the time required for any organic reaction to take place and thus "protect" the lignin.

*The Effect of Cooking with Sulphur Dioxide Solutions*

The effect of sulphur dioxide alone was investigated by making comparative runs following the same procedure as in runs Nos. 54 and 55, but using a solution of sulphur dioxide only. This solution was forced through one wood at room temperature, while the other block was being filled with water. Both blocks were then cooked loose in a cell for five hours at 140° C. after a rapid rise to that temperature.

TABLE VI

EFFECT OF COOKING WITH SULPHUR DIOXIDE SOLUTIONS ON DELIGNIFICATION

| — | No. 56 Sulphite penetration | No. 57 Water penetration |
|---|---|---|
| Lignin in product, % | 50.4 | 50.8 |

NOTE.—*Concentration of solution: free $SO_2$, 4.93%. Pressure, 10 atm.*

Both blocks were almost completely burnt, being a very dark brown or black. The wood had lost its mechanical strength and could be powdered very easily. There was no difference between the blocks.

*The Effect of Cooking with Lime Solutions*

A corresponding pair of runs was arranged using lime only with no sulphur dioxide present. This presented one novel feature, a method of getting about 1% of lime into wood in the preliminary penetration. The method adopted was to penetrate the wood thoroughly with a 5% calcium chloride solution. Then the penetrating liquid was changed to 1% sodium hydroxide, and 45

TABLE VII

EFFECT ON DELIGNIFICATION OF COOKING WITH LIME SOLUTIONS

| — | No. 58 Preliminary lime penetration | No. 59 Preliminary water penetration |
|---|---|---|
| Lignin in product, % | 31.4 | 32.8 |

NOTE.—*Solution, saturated lime water. Pressure, 7 atm.*

cc. was forced through the wood. This was just about the amount theoretically required to precipitate, as calcium hydroxide, all the calcium present in the wood as calcium chloride. Distilled water (100 cc.) was forced through to remove any excess of either calcium chloride or sodium hydroxide. Only a small amount of lime would be washed out in this treatment.

The wood which had been penetrated with lime was slightly lighter in color than the other, as though the wood which had been water-filled was burnt slightly. In neither case was there any evidence of cooking.

It is significant that in Runs 56 and 57, where no lime was present, there was the same intensive burning of the wood that was only water-filled as of the wood filled with sulphur dioxide at the start. This proved that the sulphur dioxide, or its products that caused burning of the wood, was able to penetrate satisfactorily through the wood. When lime was present in sufficient amount, as in Run 54, the wood cooked normally. If only a small amount of lime was present, such as had probably diffused into the wood in Run 55, this small amount prevented the wood from burning to any extent, but there was not sufficient to form soluble calcium salts of the lignosulphonic acids, and thus delignify the wood.

## Discussion

The work on natural penetration indicated the ease of entry of liquid into wood in a longitudinal direction as compared with either tangential or radial flow or diffusion. With regard to the shape of chips used in commercial practice, it emphasizes the advantage of short chips, and shows the least effective chip shape, variation from which in any direction will give more rapid penetration. The best shape for penetration obviously will be one in which one dimension approaches zero.

The addition of sulphite liquor to the chips in the digester surrounds each chip with solution, imprisoning the air normally in the wood. A comparison of the sinking times of sapwood specimens of various shapes, evacuated and not evacuated, showed that the air-filled wood took several thousand times as long to sink as a similar block evacuated. Though the pressure used in a digester should reduce this difference very much, the presence of air in wood is a very important hindrance to penetration.

This factor is of importance in considering the relative merits of hot or cold liquor for penetration. At a high temperature, any contained air will be in an expanded condition, occupying a larger part of the wood and allowing less of the liquor to get in. One way in which this air may be replaced by

liquid is to get it into solution. At a high temperature, the solubility of gases in liquids decreases markedly, and the likelihood of the air dissolving lessens with rise of temperature. The imprisoned air at high temperature may exert its harmful effect in a third way. The free sulphur dioxide of the sulphite liquor will go into the gaseous phase readily, leaving the solution much weaker. If the vapor phase is large, relative to the volume of liquor in the wood, sufficient sulphur dioxide may escape, so that some calcium sulphite precipitates, clogging the wood and causing a maldistribution of the lime.

On the other hand, the use of a hot penetrating liquor has certain well-marked advantages. The entry of the cooking reagents is not only by the mass movement of liquid, but there is a diffusion of both sulphite and calcium ions into and probably through the wood. This diffusion will be hastened by a rise in temperature, the rate of increase being specific for each ion. Another advantage is that at a high temperature there is less adsorption of the reagents. The work on adsorption showed that at room temperature the concentration of the liquor as it advanced into the wood would be noticeably decreased, owing to the large adsorption of sulphur dioxide, and it would be altered in relative concentration owing to the difference in adsorption between free and combined sulphite. The work on forced penetration showed that a solution low in sulphur dioxide would not penetrate so readily, so there would not only be a decrease in solute concentration but a reduced amount of solution entering the wood.

A comparison of the conflicting lines of evidence shows that the objection to the use of hot penetration (other than the technical difficulties) is all based on the presence of air. This point should be given more thorough experimental investigation.

From the experiments on delignification, it seems evident that the chief problem in penetration is to ensure a sufficient supply of lime. The free sulphur dioxide penetrates without difficulty; according to the experiments on diffusion, it enters the wood much more rapidly than the combined sulphur dioxide. The chief obstacle to the penetration of an adequate amount of lime has been found to be precipitation. This precipitation of calcium sulphite at the surface of wood has been found to occur at temperatures much lower than was commonly supposed. The work of Gurd (4) on the equilibria existing in the $SO_2$-$CaO$-$H_2O$ system gives more definite evidence of the precipitation temperature for varying concentrations. The precipitation point must not be exceeded in the early part of the process, or there will be localization of the lime, and consequent irregularity in the cook. This may be caused by local overheating or "boring." If the lime is distributed evenly through the wood, the temperature can be raised as rapidly as desired with no danger of burning. The presence of a large concentration of free sulphur dioxide prevents precipitation of the calcium salt, and also aids in its penetration. This is probably the reason underlying the recent use of solutions of high sulphur dioxide concentration.

## References

1. EDWARDES, V. P. Tech. Assocn. Pulp and Paper Inst. Proc. 4 : 22-33. 1921.
2. ENGE, L. Wochbl. Papierfabr. 54 : 245-246. 1923.
3. GRACE, N. H. and MAASS, O. J. Phys. Chem. 36 : 3046-3063. 1932.
4. GURD, G. W. Ph. D. thesis. McGill University. 1932.
5. KLASON, P. Ber. 53 : 1864-1873. 1920.
6. RICHARDSON, R. Pulp Paper Mag. Can. 32 : 160-162. 1932.
7. RICHTER, E. Pacific Pulp and Paper Ind. 2 : 66. 1928.
8. ROSS, J. H. and POTTER, J. G. Pulp Paper Mag. Can. 29 : 569-571. 1930.
9. SAUNDERSON, H., JOHNSTON, H. W. and MAASS, O. Can. J. Research, 8 : 415-428. 1933.
10. SCHWALBE, C. G. and BERNDT, K. Papier-Fabr. 24 : 250-253. 1926.
11. SCHWALBE, C. G. and LANGE, W. Papier-Fabr. 26 : 238-241. 1928.

# FURTHER INVESTIGATION OF THE PENETRATION OF LIQUIDS INTO WOOD[1]

By J. H. Sutherland,[2] H. Wyatt Johnston[3] and O. Maass[4]

## Abstract

The rate of penetration of water through heartwood, pressure and temperature remaining constant, shows an initial fairly rapid decrease followed by a gradual decrease to a constant rate. With unseasoned sapwood, the rate of penetration increases to a maximum, after which it slowly decreases. With seasoned sapwood the rate decreases with elapsed time. Pre-soaking for periods up to seven days does not affect the equilibrium rate of penetration. The initial rate is lower with pre-soaked than with air-dry wood. Pre-soaking does not hasten the attainment of an equilibrium rate. Rate of penetration is fairly constant for heartwood specimens of the same kind taken from the same transverse section of a tree. Unseasoned sapwood is more than 200 times as permeable as heartwood from the same tree. White spruce, black spruce and red pine heartwoods show about the same penetrability at low pressures. At higher pressures red pine becomes much more permeable than white spruce at the same pressure. The same is true of cedar, tamarack and balsam. Unseasoned sapwoods show increasing penetrability in the order hemlock, balsam, red pine, white spruce. Observed apparent penetration radially and tangentially through heartwood is less than 9% of that in the longitudinal direction. (Water actually penetrating was in no case greater than 1% of that penetrating longitudinally in the same time through a specimen of the same thickness.) In sapwood the rate of radial and tangential penetration is less than 2% of that in the longitudinal direction. Tangential penetration of white spruce sapwood is probably greater than radial penetration. Rate of longitudinal penetration increases with decrease in thickness of specimen. A very great increase in rate is noted after the thickness becomes less than one fibre length. This is suggested as a method of obtaining an approximation to the average fibre length. Rate is not inversely proportional to thickness, but decreases more rapidly with increasing thickness owing to loss of pressure head in passing pit membranes. Rate of penetration increases with increase in pressure differential. The rate is proportional to pressure (or slightly greater) in white spruce. The rate increases much more rapidly than proportionately with balsam, tamarack, cedar and red pine. This is due to bulging of thin pit membranes and consequent enlargement of perforations. Magnitudes of pressure and back pressure have no effect on rate of penetration, or time to reach an equilibrium rate, if pressure differential remains constant. Penetrability is not altered permanently by the application of pressure. Rate of penetration increases with temperature. Temperatures above 70° C. have a permanent effect on the penetrability. Intensive drying of wood increases its penetrability.

Sucrose solutions cause a decrease in rate of penetration greater than that expected from viscosity considerations. Molar sodium hydroxide increases the permeability of heartwood specimens of greater than one fibre length, and decreases that of sapwood and very thin sections of heartwood. Molar hydrochloric acid decreases the rate of penetration through heartwood, but has little effect on that through sapwood. Gases penetrate seasoned heartwood and sapwood easily. Pre-soaked heartwood strongly resists penetration by gases. Short lengths of unseasoned or pre-soaked sapwood are fairly easily penetrated by gases. All the evidence points to the absence of any valve action on the part of pit membrane tori.

A new theory has been advanced to account for the phenomena ordinarily ascribed to valve action, and also to explain those observations which could not be explained satisfactorily as due to torus valves.

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## Economic Importance of Penetration

The permeability to liquids is a limiting factor in the choice of wood for many practical purposes. In some of the uses of wood, penetration of liquids into the body of the wood is of very great practical importance, and either optimum conditions for this penetration or means of eliminating or reducing it are of industrial value.

For cooperage purposes, where liquids are contained in wood for long periods, the wood should be practically impermeable to the contained liquid. White oak *(Quercus alba)* wood has been found to be almost impermeable to flow across the grain of the wood, and, since it also possesses other desirable properties, it is extensively used in this industry.

In many of its uses wood is exposed to the action of fungi and insects. Treatment of the wood for preservation against destruction by these causes is desirable. This involves impregnation of the wood to a greater or less extent by such substances as creosote or zinc meta-arsenite solution. When such treatment is to be given the choice of species of wood amenable to the treatment is important.

In lumbering operations, where logs are floated by water to the sawmill or pulp mill, great losses are sustained due to sinkage of logs *en route*. Logs of some species of wood are such poor floaters that they are not cut at all. In these cases, the use of methods by which penetration of water into logs could be sufficiently retarded to permit of a larger recovery of floated logs would greatly benefit the industry.

In the manufacture of wood pulp, the wood is disintegrated into fibres by mechanical or chemical means. The latter involves the loosening of the cementing action of the middle lamella by the use of suitable chemicals. Penetration of the cooking liquor into the wood is one stage of the process, and information as to the optimum conditions for this penetration would be of practical value to the industry.

Other cases might be cited showing the importance of penetration of liquids into wood, but the above are sufficient to show the economic value of information as to the permeability of various species, and of the factors affecting penetration of various liquids into wood.

## Structure of Wood

In softwoods the predominant cell type is the tracheid (6). Tracheids are elongated cells, with tapering ends, extending parallel to the axial direction of the tree. The primary wall of a tracheid is formed by differentiation of living cells in the cambium layer of the tree. Secondary layers are laid down by apposition of new material, in the form of plates, centripetally to the primary walls. Tertiary walls may be laid down discontinuously on the secondary walls. The primary walls of adjacent cells become fused together forming what is commonly known as the middle lamella. The two most important constituents of cell walls of wood are cellulose and lignin. The

middle lamella is said (11) to contain a much larger proportion of lignin than do the secondary and tertiary walls, while the latter layers consist more largely of cellulose.

All the tracheids of a tree are not similar. In the season when growth is most rapid, the tracheids formed are relatively large, thin walled and loosely aggregated compared with those formed in the season of the year when growth is slower. These differing tracheids serve to mark out the annual rings of the tree. The thin celled part of the annual ring is known as springwood, and the thicker celled part, easily distinguishable by its denser structure and darker color, is summerwood. The transition throughout each annual ring is usually gradual.

In the original cells of the cambial layer communication between adjacent cells is provided by bundles of fibrils known as plasmodesma. These fibrils disappear when the tracheid is formed, but in the thickening of the cell walls, the areas through which fibril bundles passed do not thicken as does the rest of the wall. These thin areas, known as pits, with their perforations afford the means of communication between adjacent tracheids. In softwoods the pits are chiefly of the type known as "bordered" pits. In this type of pit the portion of wall separating the two lumina is the pit membrane. This membrane has a thickened central portion, the torus, and has numerous perforations in the marginal portion surrounding the torus. The secondary walls extend somewhat over the pit membrane but free from it, and have a perforation opposite the torus.

Adjoining tracheids overlap, at least the tapering portions where pits are usually most abundant. In softwoods, pits are largely restricted to the radial walls of the tracheids. They are so arranged that channels for longitudinal conduction of sap are provided through a series of lumina which form a more or less direct line.

The structure of wood outlined here is that given in most modern treatments of plant anatomy. Some writers differ in their view of the mode of formation of tracheids and in other details, but the authors consider this outline to give a simple and reasonable working idea of the subject.

It has been claimed that a pit membrane can act as a valve and close the pit by the torus being pressed against the pit mouth, and that this is a characteristic of water-conducting cells only.

There are two theories as to the change from sapwood to heartwood. One is that cells when first mature are most active in conduction of sap and there is a gradual slowing down of conduction until functional activity ceases, that is, it has become heartwood. The other theory is that the tracheids retain their conducting power until, for some reason, the pit membranes become closed and so prevent conduction of sap. Important changes taking place in this transformation are: the complete disappearance of protoplasts from the tracheid lumina; and withdrawal of cell sap; the water content of the cells is reduced; there are formed in, or brought into, the changing cells such new substances as oils, gums, resins, and coloring materials; and pit membranes

become fixed to a greater or less extent in the closing position. In this way the wood has become physiologically functionless and its only function is that of supporting the trees.

Other units of structure of softwoods are medullary rays and resin ducts. Medullary rays are rows of elongated cells extending in the radial direction of the wood. They have bordered pits by which they communicate with tracheids. Resin ducts are long, narrow intercellular spaces surrounded and limited by a layer of cells. They are filled with resin.

The structure of hardwoods is much more complex than that of softwoods. In the former, tracheids with bordered pits are absent, being replaced by wood fibres differing from tracheids by having thicker walls and narrow cavities, and simple pits. Vessels of indeterminate length extend as tubes longitudinally in the tree. They also occur as pores in cross sectional directions in the wood.

## Researches on Penetration of Liquids into Wood

Early research on the subject of forced penetration of liquids into wood was undertaken by those interested in preservative treatment of wood. Tiemann (23) carried on some research on the subject and drew up an hypothesis to explain the mechanism of penetration of preservative liquids into wood. Microscopical examination of impregnated wood specimens led him to conclude that liquids penetrated chiefly by passing from one tracheid lumen to the next through minute slits produced in the walls of tracheids by seasoning. He thought, as did botanists at that time, that each tracheid of fresh wood was "completely closed by the continuous primary wall." The difficulty of forcing gases or preservative into fresh unseasoned wood seemed to be satisfactorily explained by this theory. Weiss (24) explained the greater penetration of preservative into summerwood than into springwood of the same annual ring by the fact that the thick walls of summerwood tracheids would crack more than the thin walls of springwood.

Teesdale (22) of the Forest Product Laboratories at Madison, Wisconsin, carried out tests on the amenability of 20 species of conifer to preservative treatment with creosote. He found that in species where there were radial resin canals, creosote was carried by these channels and from them penetrated longitudinally in the annual rings encountered. Here radial penetration was from one-fourth to three-fourths that in the longitudinal direction. Where there were no radial resin ducts, longitudinal penetration was from 20 to 120 times as great as that radially or tangentially. In all the common species, penetration into the late summerwood was more rapid than into other parts of an annual ring, but on standing a few weeks all parts of the annual ring became uniformly treated. In the pines, spruces and some other species, sapwood is much more penetrable than heartwood. This seemed to be the case in species which had a highly developed resin system, while species having no resin ducts showed little difference in permeability between sapwood and heartwood. In some species radial penetration was greater than tangential penetration, while in others the reverse was the case.

Bailey (1) undertook to check Tiemann's observations and theories. He used more refined microscopic methods in an examination of the structure of wood. His photomicrographs showed that the slits in tracheid walls, to which Tiemann attributed the means of penetration, were present in only about 10% of a large number of seasoned wood samples examined, and where present they did not extend through the primary wall. He found that though high pressures would not force air longitudinally through long lengths of fresh unseasoned wood, it was possible to force air through pieces of more than one fibre length. He was able to force a fine suspension of carbon through sections of wood, so concluded there must be some actual opening. Refined microscopy revealed the presence of perforations in the part of the pit membrane surrounding the torus. Photomicrographs showed carbon suspension passing from one tracheid to the next through bordered pits. These results disproved the theory of Tiemann and Weiss. He explained the difficulty of forcing air through fresh unseasoned or re-soaked, seasoned wood as being due to the surface tension of the liquid in the tracheid and on the application of further pressure the closing of the pits by tori being forced into a lateral position against the pit walls. The relatively smaller penetration in heartwood than in sapwood, he explains as being due to the filling of openings in the pit membranes with resins or tori being permanently cemented against the pit walls.

The greater penetration in late summerwood of heartwood is explained as being due to the small pits in those thick walled tracheids not being closed up as are those in springwood tracheids, which are easily forced into the lateral position, and so act as valves to prevent flow.

Bailey's contribution consists in the proof of the presence of perforations in pit membranes, and in the theory that mass penetration of liquids into wood takes place chiefly by passage from tracheid to tracheid through these perforations.

*Observations from Research on Pulp*

The part played by penetration in the initial stages of cooking in the manufacture of wood pulp is recognized by the industry. Miller (9) found that the production of a good sulphite pulp was dependent on complete impregnation of the wood chips by the bisulphite part of the cooking liquor, before the digester had reached the temperature of 110° C. He found that sulphurous acid penetrated more quickly than the bisulphite, and that lignin was rendered insoluble by the action of sulphurous acid alone, above 110° C. A proper co-ordination of chip length, penetration time, concentration of acid and pressure is of fundamental importance in the production of pulp.

Birchard (4, 5), noted that penetration in the longitudinal direction of the fibres is about nine times that in the other directions. He remarks that about the same relation, between penetration in different directions, is found in preservative impregnation of wood. These relative rates of penetration determine the most economical chip size. He mentions a case in a sulphite

mill where there were a large number of long slivers among the chips. These had not been completely penetrated when cooking temperature was reached, so were not cooked.

*Research of Johnston and Maass on Penetration*

Johnston and Maass (8) studied the time rate of entry of various liquids into prepared specimens of coniferous woods, and the rate of reaction between wood and cooking liquors, both under carefully controlled conditions. A suitable apparatus for this work was designed and constructed. Experiments were carried out on a wide range of subjects in order to test the adaptability of the method to the problem, and to make a general survey of the field of penetration of liquids into wood. In several cases inconclusive results were obtained. These were not sufficiently checked owing to lack of time.

Some of the results obtained for rate of flow of water through transverse sections were employed in a theoretical and quantitative consideration of the possible modes of flow through wood. Conclusions reached from this study were that all flow in heartwood did not take place through resin ducts, but that fibre penetration is important and is fitted to explain penetration as observed.

Some general conclusions drawn from experimental results were the following: (i) the rate of flow is characteristic of the species of wood; (ii) the flow in sapwood is about 100 times faster than in the corresponding heartwood; (iii) in heartwood, longitudinal flow is about 100 times faster than flow in the radial or tangential directions; (iv) in sapwood, flow in all directions is of about the same order of magnitude; (v) no tangential flow was observed in jack pine; (vi) the rate of flow diminishes with increasing thickness of section; (vii) water, at temperatures up to 140° C. has little permanent effect on the rate of flow; (viii) hydrochloric acid decreases the rate of flow very rapidly; (ix) in unseasoned wood and in sapwood rate of flow tends to increase in proportion to the pressure; in seasoned wood rate of flow increases more rapidly than applied pressure; (x) with increasing temperature, rate of flow increases more rapidly than fluidity; (xi) the rate of flow of water tends to reach a constant value which is not permanently changed by time, temperature or pressure; (xii) there is no evidence of tori acting as valves which are closed by the application of pressure.

*Scarth's Researches*

The study of wood structure in its relation to penetrability, from the viewpoint of the botanist, was continued by Scarth (13, 14). He prepared photomicrographs of sections of wood which had been treated with mercury under pressure. These photomicrographs showed that sapwood was completely impregnated with mercury, which was seen to have penetrated from lumen to lumen through pit membranes. In the case of heartwood the mercury was shown to have entered only to the ends of tracheids which had been cut. In all cases where penetration of mercury took place, the membranes were seen to occupy the median position in the bordered pits. Where

no penetration occurred, the membranes were in the lateral position against the pit opening, thus closing the pit by means of the torus.

Scarth and Spier (16) carried on further investigation by forcing water-soluble dyes into transverse sections. In spruce sapwood the tracheids in springwood were quickly stained, while in some cases summerwood tracheids were not stained in the same time. In heartwood, summerwood tracheids permitted penetration in a short time, but considerable time was required to stain springwood tracheids.

They found that boiling in water increased the permeability of spruce heartwood. Extraction with resin solvents, followed by boiling in water, increased the permeability only to the same extent as boiling water alone. From this they conclude that pit membranes have developed direct adhesion and fusion to the pit walls, rather than simply cementation by resins.

Scarth advances the theory that pit membranes are pulled over to the lateral position owing to the presence of colloidal material in the sap. After this has taken place the sapwood, presumably, becomes heartwood. He points out, however, that non-resinous conifers, *e.g.*, balsam, have a number of unclosed pit membranes in their heartwood, and so explains the greater permeability noted in these heartwoods. The observation is made that the application of pressure may close open pits by forcing the tori over against the pit walls, and hence, mere application of pressure may decrease permeability, unless the pressure be sufficient to cause rupturing of the membranes.

The penetration in spruce heartwood is explained as due to the pits in the summerwood remaining open, but having very small perforations. He remarks that summerwood in jack pine is almost totally devoid of effective pits.

*Stamm's Work on Structural Dimensions of Wood**

Stamm (17, 18, 19, 20, 21) of the U.S. Products Laboratories, Madison, Wisconsin, employed dynamic physical and electrical conductivity methods to measure structural dimensions of the capillary openings through wood.

He first used a method based on electro-endosmotic flow of water through wood sections. From data so obtained and applied in the formula for electro-endosmotic flow, he was able to calculate the effective capillary cross-sectional area of the wood as a percentage of the total cross-sectional area. This method also gave the fibre length of the wood, as when transverse sections were used, and the rate of flow was plotted against the thickness of wood, a sharp break occurred extending from the minimum to the maximum fibre length.

Measurements of the rate of hydrostatic flow through a wood in series with a standard glass capillary tube afforded data, which, when applied in

**Stamm's earliest work was published before that of Scarth or Johnston and Maass. The summary of Stamm's work follows the others in this introduction because reports of his work are still being published.*

Poiseuille's law in conjunction with the effective capillary cross section obtained from electro-endosmotic flow, permitted calculation of the average radius of the capillary openings.

Data on the maximum cross-sectional area of capillaries were obtained by the method of applying gaseous pressure to water soaked wood sections to a sufficient extent to permit of a flow of gas, by just exceeding the force exerted by the surface tension of water in the capillaries. Jurin's law was applied to the data so obtained to directly calculate the maximum radius of the pores.

A rough check on the results obtained by these methods was afforded by forcing a colloidal mercury solution, with particles of known size, through wood. To provide more accurate results, he devised an electrical conductivity method in which he measured the electrical resistance encountered by current in flowing through sections of wood impregnated with potassium chloride solution. Reasonably good agreement was noted between results by the electro-endosmotic flow method and those obtained from this conductivity method.

## Apparatus and Technique Employed in Present Investigation

An apparatus previously used in a study of factors affecting penetration of liquids into wood was employed in a further study of the same subject. A number of changes was made in the apparatus in order to simplify procedure and to give greater accuracy in results. The most important change was the introduction of a new clamp for holding wood specimens during experiments. The procedure however has been adequately described elsewhere (8).

## Scope of the Investigation

The investigation to be described in this paper is a continuation of the research of Johnston and Maass, with particular reference to mass penetration of liquids into and through wood specimens. The effect of time, temperature, pressure, wood structure and other factors on the rate of penetration of liquids into wood was studied.

The method of study was that adopted by Johnston and Maass. Specimens of wood, of the desired species, structural nature and size, were subjected to penetration by certain liquids in an apparatus where conditions of pressure and temperature could be controlled. A standard method of preparation of wood specimens was decided on after a few runs had been carried out, so that comparisons might be made between results obtained with different woo specimens. The possibility of duplicating results and the effect of pre treatment of wood specimens were tested. During the first part of th investigation experimental runs were carried out, using seasoned white spruc *(Picea canadensis)* specimens, to study the effect on the rate of penetratio of the following factors: *(a)* pre-soaking of wood specimens for variou lengths of time, *(b)* elapsed time of penetration, *(c)* various pressures an pressure differentials, *(d)* thickness of chip, *(e)* temperature, *(f)* thre structural directions of wood, *(g)* sapwood and heartwood, *(h)* sucrose solu tions, *(i)* hydrogen ion concentration and *(j)* intensive drying.

Following the study of penetration into seasoned white spruce, the investigation went on to unseasoned wood. Red pine *(Pinus resinosa)* balsam *(Abies balsamea)*, cedar *(Thuja occidentalis)*, tamarack *(Larix laricina)*, hemlock *(Tanga canadensis)* and white spruce have been studied. Factors examined using some, or all, of these species of unseasoned wood were: *(a)* variation with time of rate of penetration into heartwood and sapwood, *(b)* effect of thickness on the rate of penetration, *(c)* effect of pressure on the rate of penetration and *(d)* rates of penetration in the three structural directions of heartwood and sapwood. The effect of hydrogen ion concentration on the rate of penetration into unseasoned white spruce sapwood was also investigated. A number of runs was carried out to check up points relating to the fine structure of wood and to theories of the mechanism of penetration through sapwood and heartwood.

## Experimental Work and Discussion of Results

*Time-rate Curves*

The first subject investigated was the variation with elapsed time of the rate of penetration of water longitudinally through white spruce heartwood. The penetration was carried out keeping driving and back pressures, and also temperature, constant throughout each run. In the first runs seasoned chips in the air-dried condition were used. These chips swell in the clamp, causing distortion and, in some cases, splitting of the chip. In order to avoid this difficulty, soaking of chips in water in an evacuated desiccator was tried as a pre-treatment. It was thought that this treatment might shorten the time required for the attainment of a constant rate of penetration, as well as eliminate distortion and breakage of chips in the clamp.

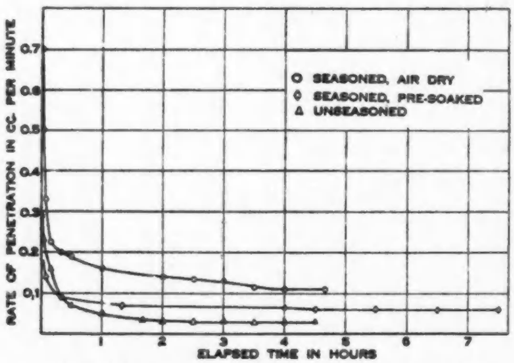


FIG. 1. *Time-rate curves for white spruce heartwood.*

Table I shows the variation with time of the rate of penetration through heartwood chips which had not been pre-soaked and also through some that had been given this treatment. Results from a run using unseasoned white spruce heartwood are also contained in the table. Fig. 1 shows graphically the variation with time of the rate of penetration for the same three cases. These curves are not to be compared with one another as to actual rates of penetration, since different pressures were used in the three cases. All three curves show that the rate of penetration rapidly decreases from the initial rate to a fairly constant rate which is attained in from two to four hours. The pre-soaked and unseasoned chips required about the same time to reach

TABLE I

VARIATION IN RATE OF PENETRATION OF WATER LONGITUDINALLY THROUGH WHITE SPRUCE HEARTWOOD—PRESSURE AND TEMPERATURE CONSTANT THROUGHOUT EACH RUN

| Condition of chip* | | Air-dry | | Seasoned | Seasoned and pre-soaked 24 hr. | | Un-seasoned |
|---|---|---|---|---|---|---|---|
| Run No. | | 7 | 8 | 155 | 9 | 66 | 131 |
| Pressure, lb./sq. in. | | | | | | | |
| Driving | | 25 | 25 | 40 | 26.5 | 70 | 60 |
| Back | | 5 | 5 | 0 | 6 | 20 | 0 |
| Differential | | 20 | 20 | 40 | 20.5 | 50 | 60 |
| Elapsed time | | Rate of penetration in cc. per min. | | | | | |
| Hr. | Min. | | | | | | |
| | 1 | | | 0.7 | | | 0.28 |
| | 2 | | | 0.5 | | | |
| | 3 | | 0.18 | 0.37 | | | 0.23 |
| | 5 | | | 0.33 | 0.40 | 0.14 | |
| | 10 | 0.16 | 0.14 | 0.25 | 0.26 | | 0.16 |
| | 20 | 0.12 | 0.12 | 0.20 | 0.24 | 0.09 | 0.09 |
| | 30 | 0.11 | 0.12 | 0.19 | 0.20 | | 0.07 |
| | 40 | 0.08 | 0.10 | 0.18 | 0.18 | | |
| 1 | 00 | 0.07 | 0.08 | 0.16 | 0.17 | | 0.048 |
| | 20 | 0.05 | 0.07 | | 0.16 | | |
| | 40 | 0.048 | 0.06 | 0.15 | 0.14 | | 0.034 |
| 2 | 00 | 0.048 | 0.053 | 0.14 | 0.12 | 0.067 | 0.031 |
| | 30 | 0.048 | 0.048 | 0.135 | 0.12 | | 0.030 |
| 3 | 00 | 0.044 | 0.048 | 0.127 | 0.13 | | 0.028 |
| | 30 | | 0.047 | 0.116 | 0.12 | | 0.027 |
| 4 | 00 | | 0.049 | 0.111 | | 0.064 | 0.027 |
| | 30 | | 0.045 | 0.112 | | 0.060 | 0.027 |
| | 32 | | | 0.12** | | | |
| | 40 | | 0.048 | 0.11 | | | |
| 5 | 00 | | | | | | |
| | 30 | | | | | 0.060 | |
| 6 | 00 | | | | | | |
| | 30 | | | | | 0.060 | |
| 7 | 00 | | | | | | |
| | 30 | | | | | | |
| 8 | 00 | | | | | 0.060 | |
| | 30 | | | | | | |
| 9 | 00 | | | | | | |
| | 30 | | | | | 0.059 | |

**All chips were [illegible] in. thick, except that used in Run 131 which was [illegible] in.*
***Chip removed from clamp and replaced with other side up.*

this constant rate of penetration as did the air-dried ones. The chips classed as unseasoned really had become partially seasoned during preparation for use.

The rate of penetration, after a constant rate had been reached, expressed in cubic centimetres per minute was considered to be the equilibrium rate for the particular chip under the conditions employed. The equilibrium rate determined in this way was used in comparing the permeability of different chips under the same conditions or of the same chip under different conditions.

Wood substance absorbs water when in contact with it. This causes the wood to swell. This swelling causes a decrease in the size of tracheid lumina and pit membrane pores, thereby decreasing the rate of penetration.

This gradual decrease in rate of penetration cannot be satisfactorily accounted for by the hypothesis of tori being forced against pit mouths, and thereby closing the pores. Nor can it be explained as due to colloidal material from the inside of tracheid lumina being carried down and deposited in the pits. In Run 155 (Table I), the chip was removed from the clamp after equilibrium had been reached, and replaced so that water entered the side from which it had previously been flowing. The rate of penetration after resumption was observed to be unchanged due to this. In Run 160 (not tabulated), a spruce heartwood chip was penetrated by water until an equilibrium rate was obtained. The inlet copper tubing of the clamp was then exchanged with the outlet tube on the other side of the chip and penetration continued with pressures as before. The same equilibrium rate of flow was observed. On again exchanging inlet and outlet tubes the same equilibrium rate was again observed. A short lag was noticed in reaching the equilibrium rate after each change in direction of flow. This would not be the action of a torus valve. A back pressure just sufficient to prevent any flow through the chip was then applied and kept on for one hour. On releasing this back pressure, penetration resumed at the same rate as that before back pressure was applied. These results show that the decrease in rate is not due to tori acting as valves, nor to deposition of colloidal material in pit membrane pores.

The lumina of tracheids are tubes of capillary size. Pit membrane pores may also be considered as shorter capillary tubes of smaller cross section. Volume of flow of liquid through capillary tubes is proportional to the fourth power of the radius of the tube. Swelling of pit membranes and internal swelling of tracheid lumina with consequent reduction in size of passages through which water can pass is sufficient to explain satisfactorily the slowing down of flow during a run. The equilibrium rate is reached when a condition of physical equilibrium has been attained between wood substance and water.

*Possibility of Duplicating Results*

Before equilibrium rates of penetration, as obtained by the method outlined, could be used to compare the permeability of different species of wood, or of different specimens of the same species, it was necessary to test the range of variation between results obtained with similar chips under the same treatment. Some of the first runs carried out gave an indication that similar chips under the same conditions gave fairly reproducible results; *e.g.*, in Runs 7 and 8 (Table I) similar chips were used, and the rates of penetration observed were approximately the same. In Table II are given the equilibrium rates of penetration observed in a number of series of runs with similar chips used in each series.

The chips used in series 4a, 4b and 4c were taken from different parts of the same short (6 in.) log. Chips used in series 6a, 6b, and 6c were also taken from the same short log. Those in 6a were from near the heart pith, 6b about 2½ in. from the pith, and 6c, 3½ in. from the centre of the log.

The results of the various series show the degree to which observed rates of penetration are reproducible in similar chips. Also in all cases similar

TABLE II

EQUILIBRIUM RATE OF PENETRATION OF WATER THROUGH SIMILAR HEARTWOOD CHIPS AT ROOM TEMPERATURE

| Series | Run no. | Thickness of chip, in. | Differential pressure, lb./sq. in. | Rate of penetration, cc./min. | Av. of series |
|---|---|---|---|---|---|
| White spruce | | | | | |
| 1 | 27 | [illegible] | 20 | 0.029 | |
| | 28 | | | 0.035 | 0.032 |
| 2 | 44 | | 50 | 0.130 | |
| | 45 | | | 0.129 | |
| | 46 | | | 0.154 | |
| | 47 | | | 0.082 | 0.124 |
| 3 | 48 | | | 0.039 | |
| | 49 | | 50 | 0.040 | 0.040 |
| 4a | 50 | | 50 | 0.070 | |
| | 51 | | | 0.074 | |
| | 53 | | | 0.071 | |
| | 54 | | | 0 052 | |
| | 56 | | | 0.045 | 0.062 |
| 4b | 55 | | 50 | 0.065 | |
| | 57 | | | 0.048 | |
| | 60 | | | 0.079 | |
| | 61 | | 50 | 0.059 | 0.063 |
| 4c | 62 | | 50 | 0.080 | |
| | 63 | | | 0.067 | |
| | 65 | | | 0.083 | |
| | 66 | | | 0.060 | |
| | 67 | | | 0.068 | 0.072 |
| 5 | 128 | [illegible] | 60 | 0.022 | |
| | 130 | | | 0.023 | |
| | 131 | | | 0.027 | 0.024 |
| Balsam | | | | | |
| 6a | 119 | [illegible] | 20 | 0.39 | |
| | 120 | | | 0.29 | |
| | 121 | | | 0.30 | 0.33 |
| 6b | 114 | | 20 | 0.26 | |
| | 115 | | | 0.40 | |
| | 116 | | | 0.26 | 0.31 |
| 6c | 122 | | 20 | 0.29 | 0.29 |

chips show a reasonably close agreement in rate of penetration. Further examples of the degree of reproducibility in results are shown in Table VI. The series from different parts of the same log show that in heartwood the permeability is of the same order of magnitude regardless of the distance from the centre of the log. This point, however, has not been sufficiently investigated to warrant definite conclusions.

The results obtained with white spruce chips show a considerable range of variation in penetrability among specimens from different trees. The difference in penetrability between white spruce and balsam is much more marked.

*Effect on Penetrability of Pre-soaking of Chips*

Though pre-soaking of seasoned chips had not materially decreased the time required for attainment of an equilibrium rate of penetration, yet it was found necessary to carry out this pre-treatment to avoid breaking and distortion of chips in the clamp. The effect of pre-soaking for various times, ranging from one to seven days was tested. Three series, of four similar chips each, were employed. These chips were soaked in water in a desiccator which was evacuated occasionally.

TABLE III

EFFECT OF PRELIMINARY SOAKING OF CHIPS ON THE RATE OF PENETRATION

| Run no. | Period of preliminary treatment in water, days | Rate of penetration in cc./min. |
|---|---|---|
| 13 | 1 | 0.062 |
| 11 | 3 | 0.092 |
| 12 | 5 | 0.075 |
| 14 | 7 | 0.041 |
| 15 | 1 | 0.030 |
| 16 | 3 | 0.030 |
| 17 | 5 | 0.018 |
| 18 | 7 | 0.035 |
| 19 | 1 | 0.018 |
| 20 | 3 | 0.018 |
| 21 | 5 | 0.020 |
| 22 | 7 | 0.022 |

*Thickness of chips, $\frac{3}{4}$ in.; driving pressure, 70 lb. per sq. in.; back pressure, 20 lb. per sq. in.; differential pressure, 50 lb. per sq. in.; temp., 23° C.*

Table III gives the results obtained for the three series of chips. The chips used in the first two series (Runs 11 to 18) were sawed off a cylinder of the required size, and were not smooth in the manner already described. The results obtained in these two series show large variations compared with the close agreement among those obtained in the third series (Runs 19 to 22) and also in the different series of runs listed in Table II.

In all these runs a constant rate was reached in about 3 hr., hence no time would be saved by prolonging the period of soaking beyond 24 hr., as this period of soaking swelled the chips and softened them sufficiently to prevent breaking in the clamp. Pre-soaking for 24 hr. was therefore adopted as preliminary treatment for seasoned chips.

*Influence of Pressure on Rate of Penetration*

The effects of pressure differential, and of magnitude of pressure on the rate of penetration were studied. Three runs were carried out using different driving and back pressures while maintaining a constant pressure differential. These runs were made at room temperature with water as the penetrating liquid. The results obtained are tabulated in Table IV. These runs show that the rate of penetration is dependent on the pressure differential and not on the magnitude of the pressures used.

A series of three runs was carried out to find if the magnitude of the pressure affected the time required to reach a constant rate of penetration. Unseasoned white spruce heartwood chips $\frac{3}{4}$ in. thick were used. The pressure differential was 20 lb. per sq. in. Results obtained for rates of penetration and time to reach equilibrium are shown in Table V.

These results show, as have nearly all runs carried out at room temperature, that a penetration time of from 3 to 4 hr. is required to reach a constant

TABLE IV

EFFECT ON RATE OF PENETRATION OF MAGNITUDE OF PRESSURE WITH PRESSURE DIFFERENTIAL CONSTANT

| Run no. | Driving pressure, lb./sq. in. | Back pressure, lb./sq. in. | Differential pressure, lb./sq. in. | Rate of penetration, cc./min. |
|---|---|---|---|---|
| 9 | 26.2 | 6 | 20.2 | 0.103 |
| | 46 | 25.2 | 20.8 | 0.098 |
| | 26.2 | 6 | 20.2 | 0.100 |
| 10 | 26.2 | 6 | 20.2 | 0.064 |
| | 45.5 | 25 | 20.5 | 0.064 |
| 70 | 40 | 0 | 40 | 0.112 |
| | 47.5 | 7.5 | 40 | 0.115 |
| | 55.5 | 15.5 | 40 | 0.113 |
| | 64.5 | 24.5 | 40 | 0.107 |
| | 70 | 30 | 40 | 0.115 |

TABLE V

EFFECT OF MAGNITUDE OF PRESSURE ON TIME TO REACH AN EQUILIBRIUM RATE OF PENETRATION

| Run no. | Pressure in lb./sq. in. | | | Time to reach equilibrium, hr. | Rate of penetration, cc./min. |
|---|---|---|---|---|---|
| | Driving | Back | Differential | | |
| 128 | 20 | 0 | 20 | $3\frac{1}{2}$ | 0.0068 |
| 132 | 40 | 20 | 20 | 4 | 0.0070 |
| 133 | 60 | 40 | 20 | 3 | 0.0065 |

rate of longitudinal penetration regardless of pre-treatment or pressures used. The close agreement in these equilibrium rates of penetration furnishes further evidence that magnitude of pressure does not affect the rate of penetration provided the differential pressure is maintained constant.

The effect, on longitudinal rate of penetration, of varying the pressure differential was shown in numerous runs on heartwood chips of the following species: seasoned white spruce, unseasoned white spruce, unseasoned black spruce, unseasoned cedar, unseasoned red pine, unseasoned tamarack, unseasoned balsam and unseasoned white pine.

The rate of flow longitudinally through wood would be expected to vary directly with the pressure head applied, if the openings remained con-

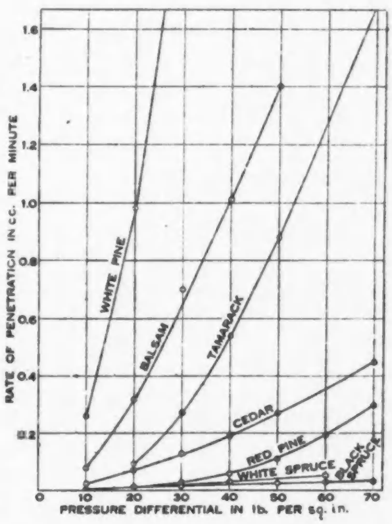


FIG. 2. *Variation with pressure of longitudinal penetration through heartwood.*

## TABLE VI

EFFECT OF PRESSURE DIFFERENTIAL ON RATE OF LONGITUDINAL PENETRATION OF WATER AT ROOM TEMPERATURE

| Run no. | Thickness of chip, in. | Rate of penetration in cc/min. at the following pressures in lb. per sq. in. | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
| **White spruce (seasoned)** | | | | | | | | |
| 23 | 3/4 | | 0.013 | | 0.026 | | 0.035 | |
| 30 | 3/4 | | 0.018 | | 0.044 | | 0.062 | |
| 32 | 3/4 | | 0.009 | | 0.026 | | 0.070 | |
| 27 | [illegible] | | 0.029 | | 0.069 | | 0.119 | |
| 28 | [illegible] | | 0.035 | | 0.095 | | 0.190 | |
| 31 | 3/8 | | 0.031 | | 0.088 | | 0.194 | |
| **White spruce (unseasoned)** | | | | | | | | |
| 128 | 3/4 | | 0.007 | | 0.015 | | 0.023 | |
| 130 | 3/4 | | | | 0.014 | | 0.023 | |
| **Black spruce (unseasoned)** | | | | | | | | |
| 172 | 3/4 | 0.003 | 0.010 | 0.014 | 0.022 | 0.025 | 0.030 | 0.032 |
| 173 | 3/4 | 0.003 | 0.011 | | 0.025 | | 0.040 | |
| **Cedar (unseasoned)** | | | | | | | | |
| 170 | 3/4 | 0.044 | 0.116 | 0.20 | 0.31 | 0.41 | | 0.64 |
| 171 | 3/4 | 0.022 | 0.06 | 0.11 | 0.17 | 0.24 | | 0.42 |
| 169 | 3/4 | 0.018 | 0.043 | 0.075 | 0.12 | 0.16 | | 0.29 |
| **Red pine (unseasoned)** | | | | | | | | |
| 109 | 11/16 | | 0.011 | 0.03 | 0.06 | 0.11 | 0.19 | 0.30 |
| 105 | 7/16 | | 0.08 | 0.23 | 0.46 | 0.56 | | |
| **Tamarack (unseasoned)** | | | | | | | | |
| 166 | 3/4 | | 0.107 | 0.33 | 0.67 | 1.07 | | 1.86 |
| 168 | 3/4 | | 0.075 | 0.20 | 0.41 | 0.68 | | 1.52 |
| **Balsam (unseasoned)** | | | | | | | | |
| 114 | 3/4 | 0.05 | 0.26 | 0.58 | 0.79 | 1.00 | | |
| 115 | 3/4 | 0.09 | 0.40 | 0.90 | 1.40 | 1.8 | | |
| 116 | 3/4 | 0.05 | 0.26 | 0.56 | 0.75 | 0.95 | | |
| 119 | 3/4 | 0.13 | 0.39 | 0.86 | 1.25 | 1.9 | | |
| 121 | 3/4 | 0.07 | 0.30 | 0.67 | 1.06 | 1.3 | | |
| 122 | 3/4 | 0.08 | 0.29 | 0.60 | 0.82 | | | |
| 176 | 1 1/8 | 0.028 | 0.11 | 0.20 | 0.31 | 0.42 | 0.51 | 0.60 |
| **White pine (unseasoned)** | | | | | | | | |
| 174 | 3/4 | 0.26 | 0.98 | 2.25 | 3.80 | | | |

stant in size. The results in Table VI and the curves in Fig. 2 show that with white spruce and black spruce the rate is approximately proportional to pressure. However, with the other species of wood the rate increases much more rapidly than in direct proportion to pressure head.* This must indicate some physical effect of pressure acting so as to change the size of the openings through which water is passing. This effect of pressure is explainable as due to the action on pit membranes through the pores of which liquid is flowing. These thin membranes are probably bulged out somewhat from their median position, thus enlarging the pores and so permitting more rapid flow.

Another possible explanation would be that the increased pressure might enlarge perforations by forcing water out of the membrane. This explanation, however, is ruled out by the results obtained with constant pressure differential with varied magnitude of driving and back pressures. Magnitude of differential pressure alone was found to effect the equilibrium rate.

Plant anatomists point out that in balsam heartwood a relatively larger number of pit membranes are in the median position than is the case in the other species tested. They also say that in spruce heartwood, practically the only pit membranes remaining in the median position are those in the latest summerwood of the annual rings. This is also the case in the heartwood of most other conifers. But in balsam heartwood about 10% of all the pits have their membrane still in the median position. It follows from these facts that many of the open pits in balsam heartwood are in thin walled tracheids. The membranes of such pits would be stretched to a greater extent than would the thick membranes of the open pits in spruce, and hence perforations in balsam membranes would be enlarged to a greater extent by pressure. A similar condition probably occurs in tamarack heartwood.

It may be that the membranes of open pits in red pine and cedar are thinner than those in spruce. The strength of wood is said to be largely supplied by the middle lamella. Pit membranes are part of the middle lamella. White spruce is a stronger wood than red pine, hence it may be that the middle lamella and pit membranes of red pine are thinner than those of white spruce in the corresponding part of the annual ring.

Runs with white spruce, red pine, cedar and tamarack chips gave no evidence of tori acting as valves which are closed by application of pressure. The pressure-rate curves, Fig. 2, for balsam heartwood, show a slight break at a pressure of 30 or 35 lb. per sq. in. This point requires further study.

Some interesting observations were made in the runs to test the effect of pressure differential. It was noted that, after a constant rate of penetration had been reached (in from 3 to 4 hr.) at a certain pressure, a constant rate was quickly attained on increasing the pressure (except in the case of some runs with balsam). This observation corroborates the conclusion drawn earlier in this section, that magnitude of pressure does not influence the time required to reach an equilibrium condition between water and wood.

**Johnston and Maass observed the same phenomenon in jack pine.*

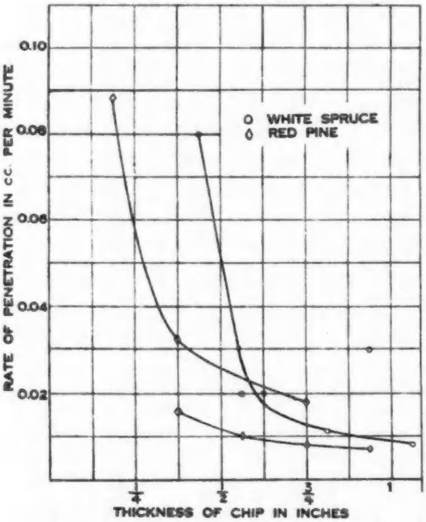


FIG. 3. *Variation with thickness of chip of rate of penetration of water longitudinally through heartwood.*

When a chip is returned from a higher pressure to a pressure at which a constant rate of penetration has already been observed, there is a slight lag in the return of the rate of penetration to the value previously noted. This lag is due to the bulged membranes requiring time to return to the equilibrium position for the reduced pressure. This eventual return to the same value is evidence against the idea of rupturing of pit membranes by pressure.

### *Influence of Thickness of Chip on Rate of Penetration*

The variation in rate of penetration with thickness of chip was investigated for seasoned white spruce and unseasoned red pine heartwoods. The results are listed in Table VII. Results

TABLE VII

VARIATION IN RATE OF PENETRATION WITH THICKNESS OF CHIP

| Run no. | Thickness of chip, in. | Rate of penetration in cc./min. with pressure differential | | Time in min. for 1 cc. penetration at | |
|---|---|---|---|---|---|
| | | 20 lb./sq. in. | 40 lb./sq. in. | 20 lb./sq. in. | 40 lb./sq. in. |
| White spruce heartwood | | | | | |
| 26 | [illegible] | 0.088 | 0.211 | 11.4 | 4.7 |
| 27 | [illegible] | 0.029 | 0.069 | 48.3 | 14.5 |
| 28 | [illegible] | 0.035 | 0.095 | 28.9 | 10.5 |
| 30 | [illegible] | 0.018 | 0.044 | 55.5 | 22.7 |
| 34 | [illegible] | 0.010 | 0.037 | 100 | 27 |
| 35 | [illegible] | 0.011 | | 94 | |
| 36 | [illegible] | 0.0062 | 0.021 | 161 | 48 |
| 37 | [illegible] | 0.0066 | 0.024 | 151 | 42 |
| 38 | [illegible] | 0.015 | 0.037 | 66 | 27 |
| 42 | [illegible] | 0.016 | 0.038 | 63 | 26 |
| 39 | [illegible] | 0.010 | 0.029 | 100 | 34 |
| 40 | [illegible] | 0.008 | 0.022 | 125 | 45 |
| 41 | [illegible] | 0.007 | 0.018 | 143 | 56 |
| Red pine heartwood | | | | | |
| 105 | [illegible] | 0.08 | 0.46 | 12.5 | 2.2 |
| 107 | [illegible] | 0.02 | 0.18 | 50 | 5.6 |
| 108 | [illegible] | 0.02 | 0.19 | 50 | 5.3 |
| 109 | [illegible] | 0.011 | 0.06 | 91 | 16.6 |
| 106 | [illegible] | 0.03 | 0.15 | 33 | 6.6 |
| 110 | [illegible] | 0.008 | 0.043 | 125 | 23 |

in the third series with white spruce (Runs 38-42) and the series with red pine are shown graphically in Fig. 3. The decrease in rate of flow is due to loss of pressure head. Resistance to flow is encountered in pit membrane pores and, to a lesser extent, in the lumina of tracheids. If the rate of flow were plotted against the probable number of pit membranes that were penetrated, the curve would be flattened out somewhat. The rate of flow does not vary inversely as thickness of chip or as number of pit membranes to be traversed, but decreases more rapidly with increasing thickness. This is due to less bulging of pit membranes and, consequently, less increase in size of pores in the membranes penetrated last, due to loss of pressure head in the pores already penetrated.

Several runs were also made using thin white spruce heartwood chips. These chips ranged in thickness from 1.5 to 4 mm. In the thinner chips (those less than one fibre length, about 3 mm. in thickness) there would be open tracheids through which water could flow without passing through pit membranes. There would also be closed tracheids, where water would have to pass through pit membranes. The data obtained in these runs are given in Table VIII.

TABLE VIII

RATE OF PENETRATION OF WATER THROUGH THIN WHITE SPRUCE HEARTWOOD CHIPS

| Run no. | Pressure, lb./sq. in. | Thickness of chip, mm. | Initial rate of penetration, cc./min. | Equilibrium rate of penetration, cc./min. |
|---|---|---|---|---|
| 142 | 10 | 1.5 | 165 | |
| 137 | 10 | 2.5 | 23.7 | 1.00 |
| 145 | 10 | 2.8 | 34.6 | 0.78 |
| 139 | 10 | 3.4 | 3.5 | 0.28 |
| 148 | 10 | 3.8 | 1.14 | 0.18 |
| 150 | 10 | 3.8 | 0.85 | 0.12 |
| 143 | 10 | 4 | 1.4 | 0.07 |
| 136 | 10 | 5.2 | 0.2 | 0.011 |

The rate of penetration is plotted against thickness of chip in Fig. 4. All the results except that obtained in Run 148 fall on the smooth curve shown. The chip used in Run 148 was faulty so that its effective thickness was really less than that shown. The sharp increase in rate noted when chips less than about 3.75 mm. thick were used is due to the presence of open tracheids in chips of that thickness. This length of 3.75 mm. is therefore about the maximum fibre length of the particular wood. Below this thickness rate of flow would be dependent chiefly on the number of open tracheids present and on the length of these open tracheids. Some flow also takes place through tracheids which have not had both ends cut off. Not more than one pit membrane would have to be penetrated in chips below this length.

The curve in Fig. 4 resembles some of Stamm's curves by means of which he estimates fibre lengths. Curves of this sort would provide another method of estimating average fibre lengths.

*Effect of Temperature on Rate of Penetration of Water through Heartwood*

The variation in rate of penetration of water through a chip at different temperatures was investigated. In two runs (44 and 45) the temperature was maintained at that of the room until a constant rate of penetration was attained. The temperature was then raised to 75° C. and held there for some time and afterwards kept at 125° C. The clamp and chip were then cooled to room temperature and the constant rate of penetration again determined. In another run (46) the rates of penetration alternately at room temperature and at temperatures from 75° to 125° C. were found. Three more runs were carried out first at room temperature, then at an elevated temperature, and lastly at room temperature again. The pressures were 70 lb. per sq. in. driving pressure and 20 lb. per sq. in. back pressure. The data from these six exploratory runs are contained in Table IX. These runs indicated that the chips were being permanently affected in some way at the higher temperatures, so that they did not return to their original permeability when brought back to room temperature. This effect appeared to depend on the temperature employed. Treatment at 75° C. did not alter these chips to any considerable extent, but higher temperatures had a marked effect.

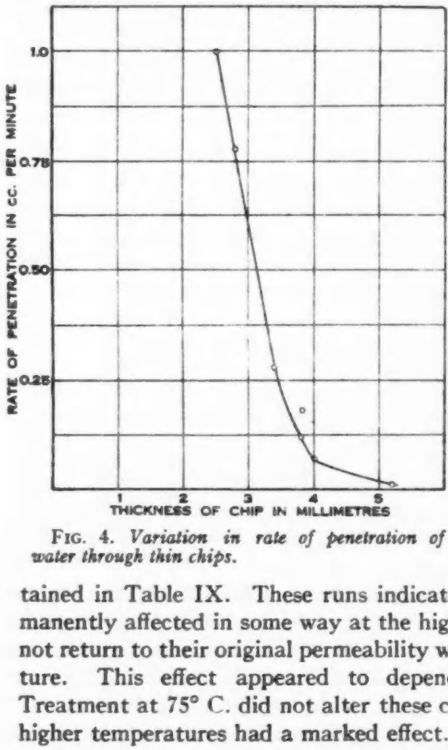


FIG. 4. *Variation in rate of penetration of water through thin chips.*

A series of runs, with similar chips, was carried out to study the permanent effect of elevated temperatures on the chip. By these experiments it was hoped to find at what temperature the permanent effect on the wood became appreciable, and at the same time to study the variation in the rate of penetration with temperature.

The chips used in these runs were ¾-in. seasoned white spruce heartwood. They were cut from three cylinders taken from adjacent parts of a short block of 18 in. diameter. Before being used they were soaked in water for 24 hr.

The first stage in each run was penetration with water at room temperature, under the same pressures as used in the exploratory runs, until a constant rate was obtained. The temperature of the chip was then raised,

by means of the heating bath, to the higher temperature (50° C. to 140° C.) at which the run was to be carried out. This temperature was maintained for one hour, during which time water penetrated under the same pressures as in the preliminary penetration. At the end of one hour, the bath was removed and the clamp and chip cooled to room temperature. Penetration was continued until a constant rate was again reached. This occurred in about 5 hr. after removal of the hot bath.

At temperatures up to 125° C. a fairly constant rate of penetration persisted during the one hour treatment. At higher temperatures the rate continuously increased during the treatment.

The results are shown in Table X and the relation between temperature and rate of penetration in Fig. 5. The average initial rate is used as the first point on the temperature-rate curve.

TABLE IX

VARIATION WITH TEMPERATURE OF RATE OF PENETRATION OF WATER THROUGH HEARTWOOD CHIPS

| Run no. | Temp., ° C. | Elapsed time at each temp., min. | Rate of penetration, cc. per min. |
|---|---|---|---|
| 44 | 23 | 320 | 0.13 |
| | 75 | 60 | 0.87 |
| | 125 | 90 | 2.5 to 2.7 |
| | 23 | 130 | 0.47 |
| 45 | 23 | 200 | 0.129 |
| | 75 | 80 | 0.71 |
| | 125 | 25 | 4.4 |
| 46 | 23 | 250 | 0.138 |
| | 75 | 40 | 0.57 |
| | 23 | 160 | 0.146 |
| | 100 | 60 | 0.83 |
| | 23 | 140 | 0.158 |
| | 125 | 70 | 3.7 to 4.0 |
| | 23 | 180 | 0.31 |
| | 125 | 70 | 4.7 to 4.9 |
| | 23 | 180 | 0.52 |
| 47 | 23 | 200 | 0.08 |
| | 100 | 250 | 0.66 to 0.72 |
| | 23 | 130 | 0.138 |
| 48 | 23 | 200 | 0.039 |
| | 100 | 480 | 0.4 |
| | 23 | 130 | 0.078 |
| 49 | 23 | 180 | 0.040 |
| | 75 | 600 | 0.20 |
| | 23 | 240 | 0.052 |

TABLE X

EFFECT OF TEMPERATURE ON RATE OF PENETRATION

| Run no. | Rate at normal temp., cc./min. | Temp. of one hour cooking, ° C. | Rate at cooking temp. | Rate after return to normal temp. | Increase in rate |
|---|---|---|---|---|---|
| 55 | 0.064 | 50 | 0.174 | 0.059 | −0.005 |
| 62 | 0.080 | 60 | 0.246 | 0.087 | 0.007 |
| 67 | 0.068 | 70 | 0.220 | 0.064 | −0.004 |
| 61 | 0.059 | 71 | 0.307 | 0.084 | 0.025 |
| 54 | 0.052 | 75 | 0.415 | 0.116 | 0.064 |
| 57 | 0.048 | 75 | 0.286 | 0.077 | 0.029 |
| 56 | 0.045 | 80 | 0.357 | 0.081 | 0.036 |
| 51 | 0.074 | 90 | 0.678 | 0.114 | 0.040 |
| 53 | 0.071 | 90 | 0.710 | 0.098 | 0.017 |
| 50 | 0.070 | 100 | 0.785 | 0.109 | 0.039 |
| 65 | 0.083 | 100 | 0.660 | 0.102 | 0.019 |
| 60 | 0.079 | 110 | 1.16 | 0.134 | 0.055 |
| 63 | 0.067 | 115 | 1.06 | 0.136 | 0.059 |
| 58 | 0.065 | 125 | 1.06 | 0.150 | 0.085 |
| *68 | 0.172 | 140 | 1.8 | 0.31 | 0.[illegible] |
| *69 | 0.132 | 140 | 2.6 | 0.49 | 0.36 |

**The chips used in Runs 68 and 69 were not from the same block of wood as the other chips.*

The increase in rate with increase in temperature is due to several factors. The viscosity of water decreases with rise in temperature, and the rate of flow, according to Poiseuille's law, varies inversely with the viscosity. Water, absorbed at lower temperatures, taken from the wood owing to the rise in temperature also tends to enlarge the perforations. Also the flow of hot water through the wood may remove in true or colloidal solution some of the material deposited in the pits. Softening of deposited resins and gums at elevated temperatures may permit greater bulging of pit membranes and hence greater enlargement of their perforations.

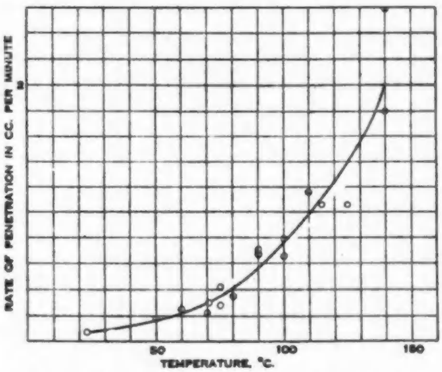

FIG. 5. *Variation with temperature of rate of penetration.*

Fig. 6 shows the permanent increase in rate of penetration due to cooking at the temperatures used. There seems to be little permanent effect of treatment of one hour duration at temperatures below 70° C. Scarth noted that permeability to water was increased to the same extent by boiling wood in water for 12 hr. as by extracting with resin solvents. The permanent effect is probably due to removal of part of the resins and gums encrusting pit membranes and clogging the perforations. Also some rupturing of membranes may take place at the higher temperatures.

*Penetrability of Sapwood*

Sapwood of most species of conifer has been found to be more amenable than heartwood to impregnation by preservatives. The penetrability of sapwood of five species was investigated during this research. The species studied were white spruce, red pine, balsam, hemlock and tamarack. These species of conifer were found to possess quite different degrees of permeability.

Flow of water was so much more rapid than through heartwood that thicker chips and lower pressures were employed. The data obtained with seven white spruce chips are given in Table XI. Data from runs using balsam, red pine, hemlock and tamarack sapwood are listed in Table XII.

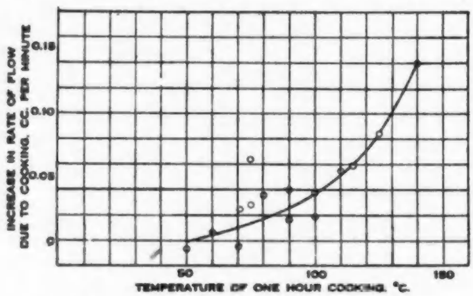

FIG. 6. *Increase in rate of penetration due to cooking one hour at various temperatures.*

TABLE XI

LONGITUDINAL PENETRATION OF WATER THROUGH WHITE SPRUCE SAPWOOD

| Moisture condition | | Seasoned | | Unseasoned | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Run no. | | 92 | 98 | 163 | 125 | 126 | 127 | 129 | 144 |
| Thickness of chip, in. | | 3/8 | 3/4 | 3/4 | 3/4 | 3/4 | 3/4 | 3/4 | 3/4 |
| Pressure, lb./sq. in. | | 3 | 10 | 1.5 | 1 | 1 | 1 | 1.5 | 1.5 |
| Elapsed time | | Rate of penetration in cc. per min. | | | | | | | |
| Hr. | Min. | | | | | | | | |
| | 02 | 0.76 | 0.09 | | 2.6 | 8.6 | 5.7 | 3.6 | 8.5 |
| | 10 | | 0.05 | 0.01 | 2.8 | 8.7 | 6.2 | 4.4 | 9.7 |
| | 20 | 0.59 | | | | | | | |
| | 30 | 0.51 | 0.04 | 0.47 | | 9.5 | 7.1 | 4.7 | 11.4 |
| | 35 | | | 2.96 | | | | | |
| | 40 | | | 2.82 | | | | | |
| 1 | 00 | 0.43 | 0.02 | | 4.30 | 10.7 | 8.6 | 5.9 | |
| | 30 | | | 1.30 | 4.35 | 10.8 | 9.6 | 6.5 | 16.4 |
| 2 | 00 | | | | 4.00 | | 9.9 | 6.5 | 16.6 |
| | 30 | | | | | | 10.0 | | |
| 3 | 00 | | | | | | 10.1 | 6.8 | |
| | 30 | | | | | | | | |
| 4 | 00 | | | | 3.0 | | | 6.4 | 16.5 |
| 5 | 00 | | | | 3.0 | 8.9 | 8.5 | 6.0 | 11.8 |
| 6 | 00 | | | | 1.6 | 8.5 | 8.3 | 5.5 | 10.2 |
| 7 | 00 | | | | 1.2 | | 8.0 | 4.9 | |
| 8 | 00 | | | 0.74 | 0.9 | | | | |
| 24 | 00 | | | 0.53 | 0.24 | 4.3 | | | |

The seasoned spruce chips behave in the same way as do heartwood chips. The rate of penetration decreases with time, but is much greater than with heartwood of the same thickness under the same pressure. Unseasoned wood, of the species tested, shows an increase in rate of penetration with time, though in some cases, after an initial decrease in rate. A maximum rate of penetration followed by a decrease in rate was observed in the runs listed in Table XII and in the runs with unseasoned chips in Table XI.

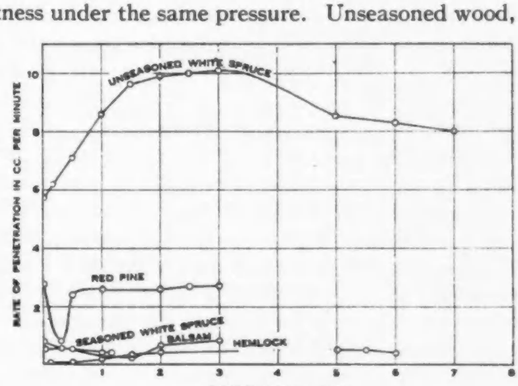


FIG. 7. *Time-rate curves for longitudinal penetration of water through sapwood.*

Time-rate curves showing graphically the variation in rate of penetration with time for one run with each species of wood used (Runs 92, 117, 99, 127 and 164) are plotted in Fig. 7.

TABLE XII

LONGITUDINAL PENETRATION OF WATER THROUGH UNSEASONED SAPWOOD

| Species | | Balsam | | Red pine | | Hemlock | Tamarack |
|---|---|---|---|---|---|---|---|
| Run no. | | 117 | 118 | 99 | 102 | 164 | 167 |
| Thickness of chip, in. | | $\frac{3}{4}$ | $1\frac{3}{4}$ | $\frac{3}{4}$ | $1\frac{3}{4}$ | $\frac{1}{4}$ | $\frac{3}{8}$ |
| Elapsed time | | Rate of penetration in cc. per min. | | | | | |
| Hr. | Min. | Pressure 1 lb. per sq. in. | | | | | |
| | 2 | 0.53 | 0.07 | 2.8 | 0.25 | | |
| | 7 | | | | | 0.015 | No appreciable penetration |
| | 20 | 0.59 | | 0.8 | 0.30 | 0.048 | |
| | 30 | | 0.06 | 2.4 | 0.42 | | |
| 1 | 00 | 0.34 | 0.07 | 2.6 | 0.78 | 0.22 | |
| 1 | 30 | 0.27 | | | 1.7 | 0.34 | |
| 2 | 00 | 0.62 | | 2.6 | 1.9 | 0.42 | |
| 2 | 30 | | | 2.7 | | | |
| 3 | 00 | 0.80 | 0.11 | 2.7 | 1.5 | | |
| 3 | 30 | | 0.15 | | | | |
| 4 | 00 | | 0.14 | | | | |
| 5 | 00 | | | | | 0.50 | |
| 5 | 30 | | | | | 0.50 | |
| 6 | 00 | | | | | 0.42 | |
| | | Pressure 10 lb. per sq. in. | | | | | |
| | 2 | 15.8 | 8.0 | | 45 | | |
| | 10 | 16.2 | | | | | |

Table XIII summarizes a large number of data relating to runs carried out with heartwood and sapwood of various species of wood. Equilibrium rates of penetration are given for heartwood specimens. Maximum rates are given for sapwood specimens for which one was found. In cases where no maximum rate was found, a rate after running some time is given. The only runs presenting a difficulty in the choice of a rate were the runs with seasoned white spruce.

From the rates given in Table XIII it is possible to compare roughly the penetrability of heartwood and sapwood of the different species. Penetration in sapwood of seasoned white spruce is from 50 to 60 times that in the heartwood from the same block. With unseasoned white spruce runs were not carried out at the same pressures for heartwood and sapwood, but by comparison of rates for other species, it is easily calculated that penetration through the sapwood of the log used is about 10,000 times that through heartwood of the same log. Unseasoned balsam sapwood allows about 230 times as much water to pass through as does the same length of heartwood. Unseasoned red pine sapwood is about 600 times as permeable as its heartwood. These ratios are at best rough approximations.

Sapwoods of the species tested differ widely among themselves in penetrability. From these results with unseasoned wood, penetrabilities of hemlock, balsam, red pine and white spruce sapwoods are roughly in the ratios

TABLE XIII

RATES OF LONGITUDINAL PENETRATION IN HEARTWOOD AND SAPWOOD OF THREE SPECIES

| Species | Run no. | Thickness of chip, in. | Pressure differential in lb./sq. in. | Rate of penetration, cc./min. |
|---|---|---|---|---|
| **Heartwood** | | | | |
| White spruce seasoned | 95 | 3/4 | 10 | 0.01 |
| | | | 20 | 0.027 |
| | (several) | 3/4 | 20 | 0.01-0.06 (Av. 0.03) |
| | (3 runs) | 3/4 | 20 | 0.008-0.018 |
| White spruce unseasoned | (4 runs) | 3/4 | 20 | 0.006-0.009 (Av. 0.007) |
| Black spruce unseasoned | (2 runs) | 3/4 | 20 | 0.010 |
| Cedar unseasoned | (3 runs) | 3/4 | 20 | 0.073 |
| Red pine unseasoned | 109 | [illegible] | 20 | 0.011 |
| Tamarack unseasoned | (2 runs) | 3/4 | 20 | 0.091 |
| Balsam unseasoned | (6 runs) | 3/4 | 10 | 0.26-0.40 (Av. 0.29) |
| White pine unseasoned | (1 run) | 3/4 | 20 | 0.98 |
| **Sapwood** | | | | |
| White spruce seasoned | 98 | 3/4 | 10 | 0.024 |
| | | | 20 | 0.075 |
| | 92 | 3/4 | 10 | 0.80 |
| White spruce unseasoned | (3 runs) | 3/4 | 1 | 4.35-10.8 (Av. 8.4) |
| | (8 runs) | 3/4 | 1.5 | 6.8-34.2 (Av. 15.8) |
| Tamarack unseasoned | 167 | 3/4 | 1.5 | No appreciable penetration |
| Red pine unseasoned | 99 | 3/4 | 1 | 2.7 |
| | 102 | 1 3/4 | 10 | 45.0 |
| Balsam unseasoned | 117 | 3/4 | 1 | 0.8 |
| | | | 10 | 16.0 |
| | 118 | 3/4 | 1 | 0.15 |
| | | | 10 | 8.0 |
| Hemlock unseasoned | 164 | 3/4 | 1.5 | 0.50 |

of 1: 1.5: 5.5: 17. Heartwoods show relative penetrabilities in order of white spruce, black spruce, cedar, red pine, tamarack and balsam in the ratios of 1: 1.4: 1.5: 10: 13: 40. This relatively great penetrability of balsam bears out the contention of the botanist that in balsam heartwood a considerable proportion of the pit membranes remain in the median position.

*Penetration in the Three Structural Directions of Heartwood and Sapwood*

The relation between rates of penetration in the longitudinal, radial and tangential directions of both heartwood and sapwood was investigated. Species of wood used were seasoned white spruce, unseasoned red pine and unseasoned white spruce. Water was the penetrating liquid used for most of these runs, but a normal solution of sodium hydroxide was used in some runs with seasoned spruce heartwood. The results obtained are tabulated in Tables XIV, XV and XVI.

The results given as the observed rates of penetration in radial and tangential directions of the wood are, at least in some cases, greater than the actual rates of penetration taking place. The penetrating liquid after enter

TABLE XIV

VARIATION IN PENETRATION WITH STRUCTURAL DIRECTION IN SEASONED WHITE SPRUCE

| Run no. | Direction of penetration | Thickness of chip, in. | Pressure, lb./sq. in. | Rate of penetration, cc./min. | |
|---|---|---|---|---|---|
| | | | | At 230° C. | At 60° C. |
| 72 | Longitudinal | 3/8 | 50 | 0.075 | 0.47 |
| 71 | Tangential | 3/8 | 50 | 0.007 | |
| 73 | Tangential | 3/8 | 50 | 0.005 | 0.02 |
| 74 | Radial | 3/8 | 50 | 0.006 | 0.018 |
| Sapwood | | | | | |
| 92 | Longitudinal | 3/8 | 20 | 1.6 | |
| 93 | Radial | 3/8 | 20 | 0.012 | |
| | | | 50 | 0.05 | |
| 96* | Radial | 3/8 | 20 | 0.016 | |
| | | | 50 | 0.052 | |
| 94 | Tangential | 3/8 | 20 | 0.04 | |
| | | | 50 | 0.09 | |
| 97* | Tangential | 3/8 | 20 | 0.008 | |
| | | | 50 | 0.02 | |

**The chips used in these runs were coated with pitch around their peripheral surface.*

TABLE XV

VARIATION IN PENETRATION WITH STRUCTURAL DIRECTION IN UNSEASONED SAPWOOD

| Species | Run no. | Direction of penetration | Thickness of chip, in. | Pressure, lb./sq. in. | Rate of penetration, cc./min. |
|---|---|---|---|---|---|
| Red pine | 102 | Longitudinal | 1 3/4 | 10 | 44.0 |
| | 100 | Tangential | 3/8 | 10 | 0.41 |
| | | | | 20 | 0.52 |
| | | | | 40 | 0.40 |
| | 104 | Tangential | 9/16 | 20 | 0.35 |
| | 101 | Radial | 3/8 | 10 | 0.08 |
| | | | | 20 | 0.11 |
| | | | | 40 | 0.23 |
| White spruce | Av. of 8 runs | Longitudinal | 3/4 | 1.5 | 15.8 |
| | 153 | Radial | 3/8 | 40 | 0.02 |
| | 154 | Tangential | 3/8 | 40 | 0.04 |

TABLE XVI

PENETRATION OF NORMAL SODIUM HYDROXIDE SOLUTION IN THE THREE STRUCTURAL DIRECTIONS OF SEASONED WHITE SPRUCE HEARTWOOD

| Run no. | Direction of penetration | Thickness of chip, in. | Pressure in lb./sq. in. | Rate of penetration, cc./min. |
|---|---|---|---|---|
| 78 | Longitudinal | 3/8 | 50 | 0.14 |
| 80 | Longitudinal | 3/4 | 50 | 0.25 |
| 79 | Radial | 3/4 | 50 | 0.001 |
| 76 | Tangential | 3/4 | 50 | 0.0012 |

ing a short distance into the wood, in a direction normal to the longitudinal direction of the tracheids, may then follow the natural path of flow of sap and so come out at the edges of the chip. This liquid entering the enclosed space around the chip, causes a pressure to be registered on the leak gauge. When the pressure around the chip attains sufficient magnitude, liquid may be forced into tracheids near the bottom of the chip and so find its way into the discharge system and appear as liquid which has actually penetrated. In order to obviate this source of error the edges of some chips were coated with hot pitch. This at least caused lower apparent rates of penetration, but the leak gauge still showed that some of the liquid entering was not actually penetrating the chip. Re-entry of liquid into the bottom of chips so treated was probably less than with untreated ones. de Khotinsky cement was used to coat the edges of the chips in the last two runs (153 and 154) of this sort that were carried out. This material formed a more closely adhering layer than did pitch, and re-entry of liquid was probably eliminated in those runs.

Very good evidence that in sapwood, penetration other than longitudinal, is appreciable was afforded in the runs carried out on unseasoned white spruce (11 runs in Table XIII and others in Table XX). In all these runs some liquid appeared in the space surrounding the chip. The pressure used (1.5 lb. per sq. in.) was too small to cause leakage at the contact of clamp and wood. In some of these runs the chips used had a layer of heartwood just outside of the part exposed to liquid. This layer was not ordinarily found to be saturated with water at the end of a run, while the remainder of the outer ring of the chip, being sapwood, was always saturated. This shows the greater resistance of heartwood to lateral penetration. In runs with heartwood, the chips did not show evidence of liquid spreading laterally.

The data in Table XIV show an approximately equal apparent penetration tangentially and radially in white spruce sapwood at both room temperature and 60° C. These rates are about 8% of the rate in the longitudinal direction at room temperature and 4% at 60° C. It must be remembered that this penetration is largely apparent. Very little water actually appeared in the discharge system. The rates are simply for water entering the surface of the chips. The rates shown by sapwood are about 10 times those for heartwood, and considerable water appeared as having penetrated the chips. No definite differentiation between rates in radial and tangential direction was given by these runs. The rates observed in those two directions are on the average slightly over 1% of that in the longitudinal direction.

In the runs listed in Table XV, red pine chips of radial and tangential section were coated with pitch around the edge, while spruce ones were coated with de Khotinsky cement. All these runs showed penetration in the tangential direction to be about double that in the radial direction. Considerable discrepancies are shown in some of these runs. In Run 100, the rate of penetration was about the same at 40 lb. per sq. in. pressure as at 10 lb. per sq. in. The $\frac{3}{16}$-in. chip used in Run 104 showed a lower rate of penetration than the $\frac{1}{8}$-in. one used in Run 100. No longitudinal rates of penetration

with chips of the same thickness, and with the same pressures, are available for comparison with these rates. However, by comparison with the thicker specimens listed, the tangential and longitudinal rates are much less than 1% of that in the longitudinal direction. The relation observed between flow in the three directions in heartwood agrees with the observation of Johnston and Maass that, in heartwood, flow in the axial direction of the fibres is about 100 times that in the other two directions. In the case of sapwood, however, there is a marked difference in the observations, since Johnston and Maass found rates of flow of the same order of magnitude in all three directions. The observation of Johnston and Maass, however, was based on only one determination of rate of flow in each of the lateral directions of the wood.

Table XVI contains some results with white spruce heartwood using normal sodium hydroxide solution as the penetrating liquid. Rates of flow in the radial and tangential directions were found to be practically equal, and less than 1% of that in the longitudinal direction.

The data for rates of flow, in other than the axial direction of the fibres, tabulated in Tables XIV and XVI, are unsatisfactory. The rates observed are probably too high in most cases. In no case would they be too low. Better results are looked for in future runs of this sort, since Runs 153 and 154, using de Khotinsky cement to prevent edge leak, were much more satisfactory than any previous runs.

The theory that penetration is largely a flow from tracheid to tracheid through bordered pit perforations explains the large difference noted between flow in the longitudinal direction and flow in the other directions. The axial dimension of tracheids is about 100 times the other dimensions. Hence, to penetrate the same distance in the radial or tangential direction, water would have to pass through 100 times as many tracheids as in a transverse section. This, of course, would be on condition that communication could be established from tracheid to tracheid to give a continuous path in radial and tangential directions. The structural peculiarity that in most softwoods, pits occur only, or chiefly, on the radial walls of tracheids would favor tangential penetration rather than radial. Also the observation that penetration in heartwood takes place most easily in late summerwood, would cause one to expect easier tangential than radial penetration. Medullary rays probably assist somewhat in radial penetration.

*Effect of Intensive Drying on the Rate of Penetration*

It has been found that air-dry chips give approximately the same equilibrium rate of penetration as do pre-soaked ones. The suggestion was made that, if wood were intensively dried, it would be impossible tc force water through it.

Three white spruce heartwood chips were dried over phosphorus pentoxide *in vacuo* (0.001 mm. of mercury) at 60° C. for three days. These chips were then penetrated at a pressure of 50 lb. per sq. in. with water. Two runs with

the air-dry wood were carried out for purposes of comparison. Results obtained are tabulated in Table XVII.

TABLE XVII

EFFECT OF INTENSIVE DRYING ON PENETRATION

| Run no. | Moisture condition of chip | Rate of penetration, cc./min. | |
|---|---|---|---|
| | | Initial | Equilibrium |
| 83 | Air dry | 5.3 | 0.72 |
| 85 | Air dry | 4.9 | 0.53 |
| 86 | Intensely dried | 5.5 | 2.6* |
| 87 | Intensely dried | 4.9 | 1.2 |

**This run was not prolonged to a constant rate.*

The results show no difficulty in penetrating the intensively dried chips. On the contrary, penetration was initially of about the same order of magnitude, but did not decrease to as low an equilibrium rate. This is probably due to some weakening or irreversible change of pit membranes owing to the loss of all their moisture.

*Penetration of Sucrose Solutions*

Some runs were carried out to test the effect, on the rate of penetration of sucrose solutions, of concentrations ranging from 1.5 to 30% by weight. In the first run (42) of this series, water was run through a $\frac{3}{8}$-in. spruce heartwood chip, under a pressure of 40 lb. per sq. in. until a constant rate of penetration was reached. This preliminary penetration was prolonged for nine hours of running time extended over two consecutive days, in order to ensure thorough saturation of the chip and hence a dependable constant rate of penetration. The water being used for penetration was then replaced by a 1.5% sucrose solution, and penetration continued with the same pressure as before, also at room temperature. After four hours of penetration with this solution, one of 3.1% sucrose was substituted. In all, five different solutions, of which the most concentrated was 14%, were used. Water was then run through for nine hours to finish the run.

The data obtained from this run, and from Run 43 with a sucrose solution of 22% concentration are shown in Table XVIII. Similar data from Run 59 which made use of 30% sucrose solution at temperatures from 24° to 100° C. are also contained in the same table. In Run 42, with each solution, the rate of penetration slowly decreased to the rate shown in the table for each concentration, where it remained fairly constant. When water was returned to the apparatus, the rate slowly increased to a value of about one-quarter of the initial rate with water. Run 43 was similar. The rate became constant in less than two hours after starting penetration. One column of Table XVIII shows the product of rate and viscosity of the penetrating liquid. If rate of flow were solely dependent on viscosity this product should be a constant, since rate of flow of liquid through capillary tubes is inversely proportional to the viscosity of the liquid. This was not found to be the case, the product decreasing continuously from that of water to that of the most concentrated solution. It was thought that possibly the effect of sucrose solutions would be to remove absorbed water from the tracheid walls and particularly from pit membranes, thus increasing the size of pores. This

increase in size of pores (if brought about) would permit a greater rate of flow (allowing for viscosity changes). This condition was not found to have been produced.

TABLE XVIII

PENETRATION OF SUCROSE SOLUTIONS INTO HEARTWOOD

| Run no. | Temp., °C. | Conc. of solution, % | Elapsed time of penetration, hr. | Rate of penetration, cc./min. | Viscosity of solution, dynes/cm². | Product rate viscosity × 10⁴ |
|---|---|---|---|---|---|---|
| 42 | 24 | 0 | 7 | 0,044 | 0.00919 | 4.04 |
| | | 1.53 | 4 | 0.020 | 0.00952 | 1.90 |
| | | 3.06 | 3 | 0.010 | 0.00987 | 0.99 |
| | | 6.11 | 3 | 0.006 | 0.01071 | 0.64 |
| | | 10.00 | 6 | 0.0044 | 0.01211 | 0.53 |
| | | 14.00 | 5 | 0.003 | 0.01331 | 0.39 |
| | | 0 | 9 | 0.011 | 0.00919 | 1.01 |
| 43 | 24 | 0 | 7 | 0.038 | 0.00919 | 3.51 |
| | | 22.00 | 3.5 | 0.002 | 0.01565 | 0.31 |
| | | 0 | 3.5 | 0.010 | 0.00919 | 0.92 |
| 59 | 24 | 30 | 5.5 | 0.055 | | |
| | 125 | | 1 | 1.06 | | |
| | 24 | | 6 | 0.150 | | |
| | 24 | | 4 | 0.011 | | |
| | 52.5 | | 2 | 0.019 | | |
| | 75 | | 1 | 0.034 | | |
| | 100 | | 1 | 0.068 | | |

NOTE.—*Thickness of chips, $\frac{3}{8}$ in.; pressure, 40 lb. per sq. in.*

Stamm, in an investigation of wood density, found that the non-electrolytes tested, of which one was glucose, were adsorbed to only a very small extent, or even negatively adsorbed by wood.

### *Effect of Hydrogen Ion Concentration on Rate of Penetration*

The effect of normal solutions of sodium hydroxide and of hydrochloric acid on penetration in heartwood and sapwood at room temperature was investigated. In the case of heartwood, seasoned white spruce chips of $\frac{3}{8}$-in. thickness were used. These were pre-soaked before being run. Similar chips were used in parallel runs with water, normal sodium hydroxide solution and normal hydrochloric acid solution as penetrating liquids. The results obtained in these runs are tabulated in Table XIX.

Fig. 8 shows time-rate curves for one run using each liquid. The curve with water is of the ordinary type, an equilibrium rate being reached in five hours. The runs with normal sodium hydroxide showed a rate variation quite different from that found with water. The initial rate was less than half that observed with water. The rate of penetration increases to a maximum in about 45 min., then slowly falls off to a constant value higher than that for water. The runs using normal hydrochloric acid show peculiarities of a different variety. The initial penetration in these cases was very rapid.

TABLE XIX

COMPARISON OF RATES OF PENETRATION AT ROOM TEMPERATURE OF WATER, NORMAL HYDROCHLORIC ACID SOLUTION AND NORMAL SODIUM HYDROXIDE SOLUTION THROUGH HEARTWOOD

| Run no. | Penetrating liquid | Duration of run, hr. | Rate of penetration, cc./min. | Remarks |
|---|---|---|---|---|
| 68 | Water | 5 | 0.172 | Time-rate curve in Fig. 8 |
| 69 | Water | 5 | 0.132 | |
| 80 | *N* sodium hydroxide | 28 | 0.250 | Time-rate curve in Fig. 8 |
| 81 | *N* hydrochloric acid | 26 | 0.100 | Result high due to leak |
| 82 | *N* hydrochloric acid | 28 | 0.053 | Time-rate curve in Fig. 8 |
| 72* | Water | 5 | 0.075 | |
| 78* | *N* sodium hydroxide | 12 | 0.14 | Time-rate curve similar to Run 80 |

**The chips used in Runs 72 and 78 were not similar to those used in the other runs listed in this table.*

The rapid rate of flow dropped in about five minutes to a rate which gradually decreased in about four hours to a constant rate lower than that with water.

Data from runs on sapwood using water, normal sodium hydroxide and normal hydrochloric acid solutions, and one of these solutions following water, are tabulated in Table XX. In all cases, where the run was with a single liquid throughout, the rate of flow increased to a value from 25 to 130% higher than the initial rate. The maximum rate was usually observed in from 50 min. to one and one-half hours after the start of the run. The initial rates (where pressure 1·5 lb. per sq. in. was used) for the three liquids showed in general that water flowed through most freely and normal sodium hydroxide most slowly. The initial rate of flow of normal sodium hydroxide solution was only about 20% of that with water. The initial rate with normal hydrochloric acid was somewhat lower than with water.

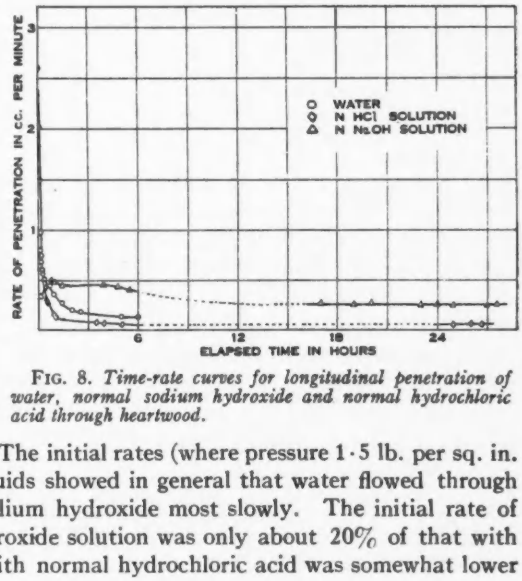


FIG. 8. *Time-rate curves for longitudinal penetration of water, normal sodium hydroxide and normal hydrochloric acid through heartwood.*

The maximum rates with water and normal hydrochloric acid solution were about 35% greater than the initial rates with those liquids. For normal sodium hydroxide the maximum rate, though actually small, was about double the initial rate.

In the runs where water was followed by normal sodium hydroxide solution, the rate of flow of caustic quickly dropped to a rate of about 15% that of

TABLE XX

COMPARATIVE RATES OF PENETRATION OF WATER, NORMAL SODIUM HYDROXIDE AND NORMAL HYDROCHLORIC ACID SOLUTIONS THROUGH WHITE SPRUCE SAPWOOD

| Run no. | Penetrating liquid | Rate of penetration, cc./min. | | Time to reach maximum rate |
|---|---|---|---|---|
| | | Initial | Maximum | |
| 144 | Water | 8.5 | 16.6 | 1 hr. |
| 129 | *N* HCl | 3.6 | 6.5 | 1 hr. 30 min. |
| 134 | *N* HCl | 1.0 | 1.6 | 3 hr. |
| 135 | *N* HCl | 20.8 | 23.2 | 1 hr. |
| 138 | *N* HCl | 7.7 | 13.8 | 1 hr. |
| 140 | *N* NaOH | 3.4 | 6.4 | 1 hr. |
| 141 | *N* NaOH | 1.3 | 2.7 | 2 hr. |
| 146 | Water | 4.7 | 10.9 | 50 min. |
| | *N* NaOH | Rate decreased in 12 min. to 1.4 cc./min. | | |
| | Water | Rate constant at 1.3 cc./min. | | |
| 152 | Water | 11.7 | 12.6 | 30 min. |
| | *N* NaOH | Rate decreased in 1 hr. to 2.0 cc./min. | | |
| | Water | Rate constant at 1.3 cc./min. | | |
| 147 | Water | 31.0 | 33.8 | 30 min. |
| | *N* HCl | Rate decreased in 40 min. to 17.2 cc./min. | | |
| | Water | Rate constant at 17.2 cc./min. | | |
| 149 | Water | 12.2 | 17.8 | 1 hr. |
| | *N* HCl | Rate constant at 16.6 cc./min. | | |
| 151 | Water | 9.0 | 13.5 | 40 min. |
| | *N* HCl | Rate remained at 13.4 to 13.8 cc./min. for 2 hr. | | |
| | Water | Rate constant at 13.3 cc./min. | | |

water. With normal hydrochloric acid solution following water, the rate of flow of acid in two cases was only slightly less than that of water, and in the other case, about 50% of the maximum rate of flow of water. The relative viscosity of the liquids must be taken into account. At 25° C. the viscosity of normal sodium hydroxide is 1.236 times that of water, that of normal hydrochloric acid is 1.060 times that of water.

The results in Table XX show the following points: sodium hydroxide, of the concentration used, penetrates heartwood more rapidly than water; hydrochloric acid, after an initial spurt, drops to a rate of flow below that of water; sodium hydroxide shows a rate of penetration lower than that of water in the case of sapwood; hydrochloric acid shows a rate of penetration into sapwood about equal to that found with water; the behavior of caustic soda seems at first glance to be anomalous.

In seeking an explanation of the action of caustic soda solution an experiment was carried out with a thin heartwood chip (1.5 mm.) from the same block as the sapwood used. The average fibre length of this wood is about 3.5 mm. so that over 50% of the tracheids of this chip would be open for flow through them without passing through any pit membrane perforations. This run was carried out with a pressure of 1.5 lb. per sq. in. Water was first forced through until a constant rate was reached, then normal sodium hydroxide until a constant rate for it was reached, after which water was again used as the penetrating liquid. Data from this run are tabulated in Table XXI.

It is a well known fact that sodium hydroxide causes more swelling of wood than does water alone. Also sodium hydroxide is a solvent for lignin. The first result of sodium hydroxide penetration might be some chemical action and solution of pit membrane material. This would have most effect on the thin membrane surrounding perforations. This would account for the initial increase in rate noted (Run 80, Fig. 8). Swelling would also be going on at the same time and would continue after solution had ceased. This swelling, chiefly in pit membranes, accounts for the gradual slowing down of penetration. The final rate with water higher than initially with water, is due to the solvent action. The difference is really higher than the rates indicate, since the viscosity of normal sodium hydroxide at 25° C. is 1.236 times that of water.

TABLE XXI

RATE OF FLOW OF WATER AND NORMAL SODIUM HYDROXIDE THROUGH A THIN HEARTWOOD CHIP (RUN 161)

| | Penetrating liquid-water | | | | | | | | | Penetrating liquid-*N* NaOH | | | | | | | | Penetrating liquid-water | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Elapsed time from start of run, min. | 2 | 4 | 9 | 15 | 21 | 25 | 34 | 40 | 50 | 53 | 55 | 57 | 66 | 78 | 84 | 116 | 122 | 130 | 145 | 175 | 192 | 210 | 270 |
| Rate of penetration, cc. per min. | 9.8 | 8.7 | 7.2 | 6.4 | 6.1 | 6.0 | 6.0 | 6.1 | 6.1 | 5.3 | 4.6 | 4.2 | 3.0 | 2.2 | 2.0 | 1.8 | 1.8 | 1.8 | 3.0 | 4.0 | 4.6 | 5.1 | 6.9 |

NOTE.—*Thickness of chip*, 1.5 *mm.; pressure*, $1\frac{1}{2}$ *lb. per sq. in.; temp., normal.*

With sapwood, the same two actions of sodium hydroxide would take place. Water causes an initial increase in rate of flow through sapwood. The same reason would cause the rate of flow of sodium hydroxide to increase, since the same solvent action around pit membrane perforations would take place. The rate of flow through sapwood is very much greater than through heartwood, hence it is clear that pit membrane perforations must be much larger. Resin ducts must also be taken into consideration. Internal swelling of tracheids takes place, and probably this swelling makes their interior area so small that a considerable resistance to flow is encountered in the tracheids. The inside walls of tracheids, being very largely cellulose, would not be dissolved to as great an extent by sodium hydroxide as would pit membranes. This internal swelling of tracheids may account for the smaller penetration of sodium hydroxide than was noted for water. The data in Table XXI show that with a heartwood chip with open tracheids the behavior of sodium hydroxide is the same as with sapwood. In the thin chip, sodium hydroxide decreased the rate after water had established an equilibrium rate. This could only be due to internal swelling of tracheids, since if only pit membrane perforations were concerned, sodium hydroxide would increase the rate of flow. No resin ducts were present in this thin chip. Viscosity difference must again be taken into consideration. According to these results it would seem that most of the resistance to flow in heartwood is encountered in pit membranes, while in sapwood, resistance in tracheids becomes considerable.

Hydrochloric acid showed a lower rate of penetration through heartwood than did water. This is due to greater swelling, and no solvent action to increase the rate. The rapid initial rate of flow observed is probably due to the absence of absorption of hydrochloric acid, so that swelling is the only action causing a retarding influence, and some little time is required for it to take place. With sapwood, hydrochloric acid seems to have about the same effect as water, the slightly lower rate being due to the greater viscosity.

*Miscellaneous Experiments*

Three runs were carried out to investigate the flow of nitrogen.

In Run 156 a $\frac{3}{4}$-in. transverse section of unseasoned white spruce sapwood was used. The chip was quite moist at the start. Five pounds nitrogen pressure was applied to the chip and caused a slow flow of nitrogen through the chip. A pressure of 10 lb. caused a flow about eight times as rapid. Some water was then run in over the chip. The water penetrated, and nitrogen flow followed. This was repeated with 20 lb. pressure with the same result. Water was run through for two hours, after which the pressure was reduced to 6 lb. and nitrogen again let in over the chip. A few bubbles of nitrogen appeared in the discharge, but flow of nitrogen soon ceased. At 10 lb. nitrogen pressures, flow started and increased three fold in 3 min.

In Run 157 a similar chip, of thickness $1\frac{1}{2}$ in., was used. Nitrogen just penetrated at 5 lb. pressure. Pressures up to 35 lb. caused increase in rate of flow.

In Run 158 a 1-in. seasoned white spruce heartwood chip was used. This chip was soaked overnight. Pressures of 20 and 40 lb. caused no flow of nitrogen. Pressure of 60 lb. caused a slow flow for four minutes, after which time flow ceased entirely. After several decreases and increases of pressure and final sudden application of 60 lb. pressure a very slow flow of nitrogen started. Water was next forced through the chip for 11 hr., during which time the rate of flow of water decreased from 0.03 to 0.018 cc. per min. After this water penetration, nitrogen was again forced in over the chip. Pressures from 5 to 60 lb. were tried but no penetration of nitrogen could be obtained.

The general observations from these runs are: (i) with sapwood of the thickness used, nitrogen flows through the green wood under a pressure of 5 lb. or less; (ii) after water has penetrated, slightly higher pressures are required to cause nitrogen penetration; (iii) with the pre-soaked heartwood used a pressure of over 40 lb. was required to cause flow of nitrogen; (iv) after penetration with water, a pressure of 60 lb. was insufficient to cause nitrogen flow; (v) these runs and the observations will be considered in a discussion of the mechanism of flow through wood.

## Discussion and Conclusions

Each phase of the subject under consideration has been discussed in conjunction with the experimental work related to it. However, some points require further consideration with reference to the complete results. The

mode of penetration of liquids through heartwood and sapwood requires some discussion. In connection with this, the evidence on action of tori as valves, which can close under pressure and so prevent or impede penetration, requires consideration.

It has been generally recognized by workers on the subject that penetration of liquids through softwoods can take place through tracheids or through resin ducts. However, resin ducts are not present in all woods, while penetration, to a greater or less extent, takes place in all woods. Also, where there are scattered resin ducts, the wood after penetration is found to be wet throughout. This could not take place without the help of agencies other than resin ducts. Water-soluble dyes have been used to follow the path of penetration (16). These, in heartwood, stained chiefly resin ducts and late summerwood tracheids while the remainder of the wood has been found to be wet by water. Also, preservative (22) was found to have slowly spread from late summerwood to the remainder of the annual ring. The wetting by water might take place owing to tracheid flow of water where dye could not penetrate, or it might be due to imbibition of water by the wood substance. Johnston and Maass point out that if imbibition were the means of flow, rate of penetration would be equal in all directions. Imbibition is a more satisfactory explanation of the spread of creosote uniformly. The use of dyes to follow the path of penetration is not entirely satisfactory, since adsorption and absorption of dye molecules by wood substance takes place, and thus interferes with penetration where this takes place to only a small extent. Hence dyes do not necessarily show where all the penetration has taken place.

In sapwood, penetration takes place much too rapidly to be accounted for by the number of resin ducts present.

The rate of penetration through a thin spruce heartwood chip (Run 161) was 6.1 cc. per min. after the chip had become soaked with water. Sapwood chips ¾-in. thick under the same pressure showed a rate of flow of from 6.8 to 34.2 (average of 8 runs, 15.8) cc. per min. In penetrating the ¾-in. chip several pit membranes would have to be passed through. Volume of flow in open tubes being proportional to length, and about 50% of the tracheids in the thin heartwood chip being open, indicated that little resistance to flow is encountered in pit membranes of sapwood, and that the tracheids themselves provide the greater part of the resistance to flow. In any case, these results would seem to indicate that there is some centripetal thickening of tracheid walls in changing from sapwood to heartwood. The similar behavior of sodium hydroxide in penetrating spruce sapwood and thin heartwood chips also indicates the same thing. Further work on this point is required before drawing definite conclusions.

*Action of Tori as Valves*

The difficulty encountered in forcing air through unseasoned or pre-soaked wood was attributed by Bailey (3) to surface tension effects when the interface between advancing air and retreating water happened to be in a pit membrane perforation. He thought this resisting force would serve to cause

the torus to be bulged away from the driving force and to close the pit by being pressed against the opposite pit mouth. With a transverse section of wood which had its tracheids filled with water, this effect could be effective in only one pit, or rather, in one series of pits, *i.e.*, most probably the ones leading into the first complete tracheids encountered. But it is quite possible to force gas through sections thicker than one fibre length, *i.e.*, where at least one series of pit membranes must be passed through. Other investigators have used the theory of valve action of tori to explain various phenomena. Thus the closing of pit membranes in the change from sapwood to heartwood has been said to be due to pit membranes being drawn into the lateral position owing to gases on one side and sap on the other. Also it has been said that excessive pressure may decrease penetration by forcing tori into lateral positions, thus closing the pits.

In the present investigation no evidence of tori acting as valves was observed either in heartwood or sapwood. On the other hand some points were observed which disprove the theory in cases where such action might be expected.

In Runs 156, 157 and 158 nitrogen was used in testing the permeability of sapwood and heartwood to gas. With sapwood no great difficulty was encountered, since a pressure of less than 10 lb. per sq. in. was sufficient to cause flow of nitrogen through a 1½-in. chip. With heartwood it was different. A pressure of 60 lb. per sq. in. was sufficient to cause flow for a few minutes through a partly pre-soaked chip (Run 158) but flow soon stopped, but was resumed after several decreases and increases of pressure. This is not the action of a valve. Later a pressure of 60 lb. per sq. in. was insufficient to cause any flow of nitrogen. Gases flow freely, longitudinally, through heartwood in which there is no free water present. Water also flows through under reasonable pressures. Water flows easily after flow has been stopped by application of gas pressure to wet wood. These facts do not point to the presence of anything that can supply valve action.

The surface tension action at membrane perforations does not explain the reason for the large increase in resistance encountered as the thickness of the wood section being penetrated is increased. This can be explained more satisfactorily in conjunction with a manifestation of the force of surface tension in a different way. Each of the tracheids in a series forming a passage through the wood may act as a Jamin's tube, or as part of one formed by intercommunicating tracheids. A Jamin's tube is a capillary tube in which are arranged alternately drops of liquid and bubbles of gas. A pressure exerted at one end of the tube causes adjustment of the menisci between liquid and gas so that each drop of liquid transmits less pressure than it receives. The resistance is proportional to the length of the tube and the number of sequences of drop of liquid and bubble of gas. Such a series of detached drops would be produced on the entry of gas into water-soaked wood. A pressure of 60 lb. per sq. in. was sufficient to initiate a flow of gas. This flow would carry down water from the soaked upper part of the chip to

the interior of the chip where there was no free water, thus lengthening the "Jamin's tube." (The chip was pre-soaked in water without the use of a vacuum.) This increase in resistance might be sufficient to cause cessation of flow, which was actually noted. The resumption of flow noted was due to absorption in the interior of the chip of the droplets formed there, hence again shortening the "Jamin's tube." This cycle could not be repeated after water had penetrated and swollen the chip, since absorption of water would not take place to shorten the Jamin's tube. Internal swelling of tracheids and of pit membranes would also tend to reduce the rate of flow, since in smaller tubes the Jamin effect would be more marked. The low pressure required to force nitrogen through wet sapwood in contrast to the much greater resistance of wet heartwood is due to the larger tracheids in sapwood. This theory fits the observed facts much better than does the one which postulates pit closure by tori.

The rate-pressure curves shown in Fig. 2 show a regular increase in rate with increase in pressure. No discontinuity which could be traced to valve action of tori is noted in these curves. In one run (99) with sapwood the pressure was suddenly increased from 1 to 40 lb. per sq. in. This increase, far from causing a decrease in rate of flow, increased the rate of penetration to 100 times its original value. In several runs, after an equilibrium rate of penetration had been attained, the chip was turned over, or liquid pressure exerted from the opposite end. This change caused no change in the rate of penetration. In another run, after attaining an equilibrium rate of penetration, a back pressure sufficient to prevent any flow was applied for one hour. On removing the back pressure, penetration resumed at the same rate as before. A few chips were re-run after having been air-dried for nearly a year. Rates of penetration noted in two cases were similar to those when first run. Another showed a higher rate.

Photomicrographs supply visual evidence that heartwood differs from sapwood in that most of the pit membranes are sealed in the lateral position. Penetration data tend to corroborate this evidence. Botanists are not agreed as to the cause of this pit closure in the growing tree. It has been shown that closed pits have their tori sealed in the lateral position by actual adhesion, rather than by simple cementation. During this investigation no evidence was obtained to show that pits could be closed by artificial means, in fact any evidence on the subject pointed to the absence of any such closure.

## References

1. Bailey, I. W. Forestry Quart. 11 : 5-11. 1913.
2. Bailey, I. W. Forestry Quart. 11 : 12-20. 1913.
3. Bailey, I. W. Am. Ry. Eng. Assocn. Bull. 174. 1915.
4. Birchard, W. H. Paper Trade J. 85 : 59-61. 1927.
5. Birchard, W. H. Can. Chem. Met. 12 : 31-34. 1928.
6. Eames, A. J. and MacDaniels, L. H. An introduction to plant anatomy. McGraw-Hill Book Co. New York. 1925.

7. Hawley, L. F. and Wise, L. E. The chemistry of wood. Chem. Cat. Co. New York. 1926.

8. Johnston, H. W. and Maass, O. Can. J. Research, 3 : 140-173. 1930.

9. Miller, R. N. Chemistry of the sulphite process. Tech. Assocn. of the Pulp and Paper Industry, 1928.

10. Poynting, J. H. and Thomson, J. J. A text-book of physics. Vol. 1. J. B. Lippincott. Philadelphia. 1905.

11. Ritter, G. J. Ind. Eng. Chem. 17 : 1194-1197. 1925.

12. Ritter, G. J. Ind. Eng. Chem. 20 : 941-945. 1928.

13. Scarth, G. W. Paper Trade J. 86 : 53-56. 1928.

14. Scarth, G. W. Pulp and Paper Mag. Can. International No. 129-132. 1928.

15. Scarth, G. W. and Gibbs, R. D. Can. J. Research, 3 : 80-93. 1930.

16. Scarth, G. W. and Spier, Jane D. Trans. Roy. Soc. Can. 23 (V) : 281-288. 1929.

17. Stamm, Alfred J. Electroendosmosis through wood membranes. Colloid Symposium Monograph, 4 : 246-257. 1926.

18. Stamm, Alfred J. The structure of softwoods as revealed by dynamic physical methods. Colloid Symposium Monograph, 6 : 83-108. 1928.

19. Stamm, Alfred J. J. Phys. Chem. 33 : 398-414. 1929.

20. Stamm, Alfred J. J. Phys. Chem. 36 : 312-325. 1932.

21. Stamm, Alfred J. J. Ind. Eng. Chem. 24 : 51-53. 1932.

22. Teesdale, C. H. U.S. Dept. Agr. Bull. 101. 1914.

23. Tiemann, H. D. Am. Ry. Eng. and Main. of Way Assocn. Bull. 120. 1910.

24. Weiss, H. F. Proc. 8th Ann. Meeting Am. Wood Preservers' Assocn. 159-187. 1912.

# AN INVESTIGATION OF SEMI-MICRO KJELDAHL METHODS[1]

By J. A. Scarrow[2] and C. F. H. Allen[3]


## Abstract

It is shown that the estimation of nitrogen by the Kjeldahl method on a semi-micro scale is more sensitive to variations in procedure than the corresponding macro method.

Several methods of preliminary reduction, recommended for certain types of compounds, have been found difficult to adapt to semi-micro work. A method of reduction, involving use of hydriodic acid and phosphorus, has been developed for many such compounds.


A volumetric method for estimating nitrogen in organic compounds is very desirable. The Kjeldahl method, which is commonly used, works satisfactorily for most simple amines, but is not reliable when applied directly to several classes of compounds (6) such as those containing N-N, N in a ring or polynitro compounds.

In applying the method in this laboratory to 2,4-dinitrophenylhydrazones of various carbonyl compounds, it was found that low results were occasionally obtained with derivatives of known structure. Since these invariably gave correct results by the Dumas method, it seemed probable that the Kjeldahl procedure might be modified so as to adapt it for use with these exceptional hydrazones. A series of experiments was carried out to test the effects obtained from variations in the concentration of the sulphuric acid, potassium sulphate, and glucose. The suggested semi-micro method (1) was found satisfactory except that a few compounds gave better results when more potassium sulphate was used. Since this increased concentration of potassium sulphate did not appear to affect other results, it has been incorporated into the writers' present procedure (Method *A*). Use of catalysts such as selenium, magnesium, and mercury was also tested with no instance of improvement being noted, although these have been shown to be useful in digestion of bulky plant materials (7), where they aid probably by getting rid of the large mass of organic material within a reasonable time. Since simple nitrogen compounds can be digested within 1½-2 hr., provided sufficient potassium sulphate is present, no useful purpose is served by addition of catalysts of this type. Where the nitrogen content runs to 20% or higher, a digestion period of at least 1½ hr. appears to be necessary. Using the concentrations recommended in Method *A*, and heating with a Bunsen burner, samples of animal charcoa were brought to a pale blue in 20–30 min. Such rapid digestion is not advisable since low results invariably follow. Prolonged heating, on the other hand, tends toward slow loss of nitrogen as nitrogen gas (2, 8, 9). This would indicate that this important variable is frequently not defined with sufficient accuracy.

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Preliminary reduction was also tested by a series of runs involving the use of sodium thiosulphate (5), sodium hydrosulphite ($Na_2S_2O_4$) (6), and zinc dust (3, pp. 407-433). None of these gave satisfactory results with hydrazones, and in some cases lower results were obtained than by the use of glucose alone.

It is to be noted that no recent use has been made in this connection of the powerful reducing action of hydriodic acid and phosphorus. A trial run using these gave a comparatively good result; this led to further work being done to devise a method for their utilization. This method, in the writers' opinion, is much superior to others of this type which were tried.

## Preliminary Reduction with Hydriodic Acid and Phosphorus

Because of the many possible variations, a large number of runs was necessary.* Some of the results of these are not satisfactory as analyses, but are included as they enable comparisons to be made among different methods. A fairly general method was developed which was satisfactory for all 2,4-dinitrophenylhydrazones and guanidines available and this is given as Method *B*. In all cases investigated this method gave consistently better values than any other involving a preliminary reduction. The procedure in Method *B* was satisfactory for nearly all the compounds analyzed. For a few exceptional compounds it is necessary to vary the period of reduction. Thus *o*—oxyquinoline sulphate was satisfactorily reduced by just bringing the hydriodic acid to a boil over a small shielded flame, and hexamethylenetetramine was best reduced by heating on a steam bath for five minutes. The method failed, however, with dicyanodiamide and with semicarbazide salts. Dicyanodiamide (calcd., 66.6%N) gave yields of 50.0, 54.2 and 52.4% of its nitrogen content when analyzed by Method *A*. This is interesting from the point of view of Werner's formula (10, p. 86), in which this substance is indicated as containing three amino- and three ring-nitrogen atoms.

Method *B* was tested without alteration on several other compounds having nitrogen in a ring, such as cyclonite† which gave a low result, and on indole, carbazol, and mercaptobenzothiazol, all of which gave nearly their theoretical values.

Simple nitrogen compounds, such as amines, amides, oximes, nitro, and dinitro derivatives do not require a preliminary reduction and for these cases Method *A* gives reliable results.

## Method *A*

*For Simple Nitrogen Compounds*

A mixture, made up of 0.02-0.03 gm. of substance, 0.1 gm. of copper sulphate, 7 gm. of potassium sulphate, 2 gm. of glucose, and 15 cc. of concentrated sulphuric acid was digested until colorless, the heat being regulated from time to time when necessary so that this occupied 1½-2 hr. After cooling,

**The present paper is based on results from 150 determinations.*

*†The above are given to indicate changes which may be necessary in order to adapt the method to a single difficult compound, such as occurs in control laboratory work.*

it was carefully diluted with 150 cc. of distilled water and again cooled in running water. A 24-gm. stick of sodium hydroxide was then added to the flask which was attached immediately to the stillhead, and the ammonia distilled over until violent bumping began. It was found most convenient to weigh the sample on a cigarette paper and put the whole into the flask. Sodium hydroxide, $0.02N$, and sulphuric acid of about equal strength were found satisfactory. Titration was carried out in presence of alizarin or of methyl red as individually preferred.

## Method *B*

*For Dinitrophenylhydrazones and Guanidines*

A mixture of approximately 0.05 gm. of red phosphorus and 2 cc. of concentrated hydriodic acid (of about 45% strength and usually not iodine-free) was heated to fuming in a 300-cc. Kjeldahl flask held in an upright position on a steambath, the flask being set on a 2–3 in. opening. A 20-gm. sample, wrapped in a cigarette paper was then dropped into the hot liquid. As soon as the paper became disintegrated, a crystal of phenol (0.1–0.2 gm.) was added. The flask was removed from the steambath and immersed in cold water after the sample had been in contact with the hot hydriodic acid for 15–20 min.

A mixture of approximately 0.1 gm. of copper sulphate and 7 gm. of potassium sulphate was then added, followed by 15 cc. of concentrated sulphuric acid, a few drops at a time, and with cooling and shaking. The whole was digested as usual, starting with a low flame for 15 min. and then increasing the heat stepwise so as to complete the digestion in 1½-2 hr. The procedure from this stage was the same as in Method *A*.

## Notes

1. The iodine which forms occasionally causes bumping during digestion; this may necessitate addition of a piece of porous tile. The iodine may be recovered as such, or allowed to escape. In any case it must be driven completely out of the flask before the caustic is added. A second burner may be used to remove the iodine in the neck of the flask if necessary.

2. A minimum of wash water should be used to ensure a sharp color change in titration.

3. A result was considered satisfactory if it lay within 0.5% of the theoretical. For purposes of identification, or of ascertaining the number of nitrogen atoms present, a greater deviation is often permissible (6). For many compounds the Dumas* method must be used. Here again however dinitrophenylhydrazones and those compounds having nitrogen in a ring, *e.g.*, antipyrin, require at least double the time necessary to completely burn a simple amine.

**W. M. Lauer and C. J. Sunde (4) have devised a very successful semi-micro modification of the Dumas method, and have used it to analyze several compounds with a maximum deviation of 0.4% from theoretical values.*

TABLE I

COMPARISON OF METHODS

| Compound | Nitrogen, % | | | | | |
|---|---|---|---|---|---|---|
| | Calcd. | Standard method *A* | Reduction with zinc | Reduction with $Na_2S_2O_4$ | Standard method *B* | Dumas method, semi-micro |
| 2, 4-Dinitrophenylhydrazine | 28.3 | 21.8 | — | 21.0 | 27.6 | 28.2 |
| ω-Methoxyacetophenone 2, 4-dinitrophenylhydrazone | 16.9 | 16.4 | 12.5 | 14.8 | 16.8 | — |

TABLE II

COMPARISON OF METHODS *A* AND *B*

| Compound | Nitrogen, % | | | |
|---|---|---|---|---|
| | Calcd. | *A* | *B* | Dumas |
| 2, 4-Dinitrophenylhydrazone of: | | | | |
| Menthone | 16.7 | 16.1 | 16.4 | — |
| Methyl *i*-hexyl ketone | 18.1 | 15.9 | 17.6 | — |
| Cyclohexanone | 20.0 | 17.6 | 20.0 | — |
| γ-Benzoylbutyrolactone | 15.1 | 13.4 | 15.0 | 14.8 |
| γ-Chlorobutyrophenone | 15.4 | 13.4 | 15.1 | 15.8 |
| *n*-Butyroin* | 17.2 | 15.6 | 17.3 | 17.5 |
| Guanidine hydrochloride | 44.0 | 41.5 | 43.5 | — |
| Nitroguanidine | 49.9 | 48.5 | 50.1 | — |
| Diphenylguanidine | 20.0 | 18.9 | 20.5 | — |
| Carbazol | 8.4 | 7.5 | 8.2 | — |
| Di-*o*-nitrophenyldisulphide | 9.1 | 4.2 | 9.1 | — |
| Mercaptobenzothiazole | 8.4 | 8.1 | 8.6 | — |
| *p*-Aminoazobenzene | 18.0 | — | 17.5 | — |
| *p*-Nitrosodimethylaniline | 18.6 | — | 18.8 | — |
| *o*-Oxyquinoline sulphate† | 5.8 | 1.8 | 6.1 | — |
| Hexamethylenetetramine§ | 40.0 | 37.0 | 39.2 | — |

**n*-Butyroin 2, 4-dinitrophenylhydrazone gave 14.5 and 14.3% N by the Kjeldahl method (1) when 2 gm. of potassium sulphate was used, whereas method A using 7 gm. gave a somewhat higher value.*

†*Reduced by being brought just to boiling over a small shielded flame.*

§*Reduced by heating on the steam bath for five minutes.*

## References

1. ALLEN, C. F. H. J. Am. Chem. Soc. 52 : 2955-2959. 1930.
2. FLEURY, P. and LEVALTIER, H. Bull. soc. chim. 37 : 330-335. 1925.
3. LASSAR-COHN. Organic laboratory methods. Williams and Wilkins Company, Baltimore. 1928.
4. LAUER, W. M. and SUNDE, C. J. Mikrochem. Pregl Festschr. 235-242. 1929.
5. RANKER, E. R. J. Assoc. Official Agr. Chem. 10 : 230-251. 1927.
6. SISLEY, P. and DAVID, M. Bull. soc. chim. 45 : 312-324. 1929.
7. TAYLOR, L. V. Ind. Eng. Chem., Anal. Ed. 5 : 263. 1933.
8. VAN DAM, W. Rec. trav. chim. 14 : 208-215. 1895.
9. VEIBEL, S. Bull. soc. chim. 41 : 1410-1416. 1927.
10. WERNER, EMIL A. The chemistry of urea. Longmans, Green and Company, London. 1923.

# COMPETITIVE EFFICIENCY OF WEEDS AND CEREAL CROPS[1]

By T. K. Pavlychenko[2] and J. B. Harrington[3]

## Abstract

The results of a study of the competing abilities of certain weeds and crop plants are presented. Characteristics studied as possible indicators of competitive efficiency were development of assimilation surface, stomatal number, readiness and uniformity of seed germination and distribution and penetration of root systems.

It is shown that success in competition depends on readiness and uniformity of germination under adverse moisture conditions, the ability to develop a large assimilation surface in the early seedling stage, the possession of a large number of stomata and a root system with a large mass of fibre close to the surface but with its main roots penetrating deeply.

Cereal crops were classified in the order of competing ability as follows:—barley, rye, wheat and oats, flax. *Brassica arvensis* and *Avena fatua* were the most vigorous competitors among the weeds studied.

The farmer has to deal with crops and weeds under many soil and climatic conditions. Both of these groups of plants live in the same environment, and their productive capacities are limited by the moisture, light, nutrients and space available. Each group makes a specific claim upon the productive powers of the field. The competition between them is not very obvious to the casual observer and is therefore easily overlooked. This may explain why competition in cultivated fields has not received due consideration until recently. The struggle is frequently detrimental to crop plants and a weedy harvest results. On the other hand a clean crop may be due to the presence of relatively few weeds, or it may demonstrate the smothering ability of the crop. The latter point is not always appreciated.

According to Clements, Weaver and Hanson (8) the problem of competition in field crops "is centered upon the relative merits of species and varieties in terms of competitive adaptation to seasonal and annual cycles and to the tillage and rotation control of factors and reactions." Each weed and each species of crop has its own merits of competitive adaptation and its own reactions towards its rivals.

For practical purposes the competitive features of both weeds and crops should be studied under definite soil and climatic conditions. Results obtained in investigations along these lines at the University of Saskatchewan from 1930 to 1932 are presented here.

## Literature Review

Studies among plant communities and among plants in homogeneous populations have shown that competition is a powerful natural force tending toward limitation or extinction of the weaker competitors. The effects of competition were noted in forest communities by De Crescentiis (10), in the

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plant kingdom generally by De Candolle (9) and in nature as a whole by Charles Darwin. Nägeli (21), 1874, suggested that the probable number of individuals of a competing species in a given habitat is determined by the average life-period and average annual increase.

Early concepts of competition were based on observation of natural forest and grassland communities. In 1903 Clements began systematic research under controlled conditions in an attempt to explain not only the role of competition but also its nature, cause and extent, as well as the parts played by the above and underground parts of the plants. He and his coworkers (4-8) show that "competition is purely a physical process" which "arises from the reaction of one plant upon the physical factors about it and the effect of these modified factors upon its competitor"; that "not only does a small advantage in root, culm or leaf improve the response and hence the chances of the parent plant, but it also encourages the production of tillers, which are potential individuals and constitute what is virtually a reinforcement in the contest"; that "the most important features of the life-forms conditioning the success in competition are, duration or perennuation, rate of growth (top and roots), rate and amount of germination, vigor and hardiness," and that "absorption, transpiration, photosynthesis, chemosynthesis and respiration all affect the physical factors of the habitat directly, producing reactions that determine the course, intensity and outcome of competition." They state also that among the physical factors affecting competition, water is paramount, light next and nutrients third in importance. They point out that "with field crops the problem is centered upon the relative merits of species and varieties in terms of competitive adaptation to seasonal and annual cycles and to the tillage and rotation control of factors and reactions," and that the outcome of competition is equilibrium or dominance of one competitor or extinction of the weaker.

Montgomery (20) studied the competitive abilities of cereal crops. He found, for instance, that Turkey Red wheat is a much stronger competitor than Big Frame wheat. He states that a small admixture of the former in a sample of the latter increased rapidly and in a few years produced 90% of the total stand.

Kiesselbach (19) found that the yield of plants of a given variety fluctuated within broad limits as a result of differences in spacing or surrounding growth. Aaltonen (1) emphasized the importance of the underground parts of field crops in competitive reactions. Sukatschew (22) showed that some biotypes which are vigorous competitors in open cultures do poorly in dense ones.

Brenchley (3, pp. 159-174) in studies of the association of various weeds with cultivated crops found that certain weeds occurred more or less regularly in association with definite field crops, that some weed species were never found with certain crops, and that certain weeds were more or less common among all cultivated crops. She explained this as follows: "One of the chief factors in determining the abundance or scarcity of a particular weed is the degree of competition it is able to withstand successfully, and furthermore, the aboveground struggle for light is as important as the underground struggle for food and water."

Hopkins (13-17) and Barnes and Hopkins (2) have shown by experiments carried on over a period of years at the Dominion Experiment Station, Swift Current, Saskatchewan, that the yield of wheat may be reduced as much as 50% as a result of competition with weeds.

Hanson (12) reports on observations on competition between blue grama and porcupine grasses, on the one hand, and mountain-sage on the other. In the course of several years the mountain sage gained the upper hand and replaced the valuable forage grasses.

Hopper (18) directs attention to the problem of subduing weeds by including in rotations crops which compete vigorously with troublesome weeds. Hanson (11, p. 9) shows that one week's difference in time of cutting alfalfa for hay has a decisive influence on the ability of the following crop to compete successfully with weeds.

From the foregoing review it is obvious that the general significance of the problem has been explained. Investigations have illustrated dominance in admixture, and reactions under field conditions between related plants and other vegetation. Competition between weeds and crop plants presents a useful field of research which, if carried out in great detail, should be of considerable practical significance. Results of practical value can be obtained only by application of a knowledge of the underlying principles coupled with studies of the relative competing efficiencies of weeds and crops.

## Scope of Work

It was recognized in this work that there is no such thing as weed-free cultivated land. Field observations carried out for several years showed that every field seeded to a cereal crop supported a mass of seedlings of annual weeds when the crop was about 3 in. high. At harvest a number of these fields bore clean crops. The grain crops had smothered the weeds completely. Other fields of the same or different crops, or seeded at different rates and dates, produced a weedy and scant crop, the weeds having proved more efficient competitors under existing conditions. The determination of the degree of competitive efficiency of each weed and the reasons therefore was the main object of this study.

In competition supremacy may be attained by the species or variety which is able, by virtue of greater physiological activity and morphological adaptability, to utilize the environment most efficiently. Rate of growth may be the best manifestation of such efficiency. Readiness and uniformity of germination, if characteristic of a species or variety, may be of considerable importance. Similarly, facilities for the absorption of water and nutrients and for the assimilation of carbon dioxide may be important factors. These facilities involve all of the plant, including the underground portion. With these points in mind, studies were made of rates of growth, readiness and uniformity of germination, total assimilation surfaces and root development of weed and crop plants.

In 1930 the following weed and cereal plants were studied: weeds:—wild oats *(Avena fatua)*, wild mustard *(Brassica arvensis)*, tumbling mustard *(Sesymbrium altissimum)*, stinkweed *(Thlaŝpi arvense)*, lamb's-quarters *(Chenopodium album)*, redroot pigweed *(Amaranthus retroflexus)* and wild peppergrass *(Lepidium intermedium)*. Cereals:—Marquis wheat, Prolific spring rye, Hannchen and Sol barley, Banner oats and Crown flax. There were added in 1931, hare's-ear mustard *(Conringia orientalis)*, blue bur *(Lappula echenata)*, wild buckwheat *(Polygonum convolvulus)* and cow cockle *(Vaccaria vulgaris)*; and in 1932 Reward, Reliance and Garnet wheat, Colsess, Regal and Trebi barley and Gopher oats.*

## I. Rate of Growth Study

In each of three years (1930-1932) the cereals were grown in competition with the weeds listed for that season. As many as seven trials were used to allow of observation of the behavior of both crop and weed plants under different moisture and temperature conditions. The plots consisted of 8-ft. drill rows, 6 in. apart, seeded at the ordinary rates and depths. The arrangement as shown in Fig. 1 allowed for alternating check and competition plots. Thus there were two checks for comparison with each competition plot. Each competition plot consisted of two rows of the weed with a cereal row between them.

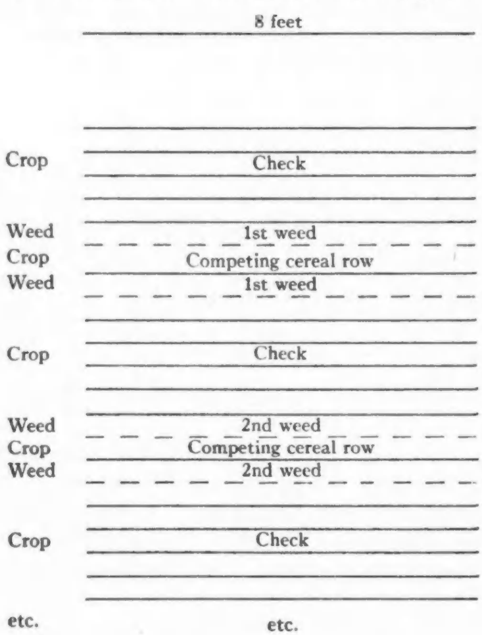



FIG. 1. *Plot layout in competitive study.*

The plants in the four central feet of each check, competing-crop, and weed row were hand pulled at harvest time and cured. The portion of the plant which had been above ground was cut off and used for rate of growth determinations. Data were compiled on weight of seed, weight of straw, total air-dry matter, height and maturity. These were supplemented by notes taken during the growing season on date and percentage of emergence, dates of heading, blooming and maturity and heights at intervals of approximately ten days throughout the season.

**Marquis, Reward, Garnet and Reliance are hard red-seeded, spring sown varieties; Banner is a mid-season, white seeded, open panicle variety; Colsess and Sol are hooded, hulled and six-rowed; Trebi and Regal are awned, hulled and six-rowed*

In order to provide material for comparison a single row of each crop and weed species was grown. These rows were planted 45 in. apart in order to eliminate interspecific competition. In addition single plants were grown each in an area of 100 sq. ft. This allowed the plants complete freedom from competition of any sort. Data from all of this material provided the basis for an estimation of the competitive ability of the different species.

*Results*

Since the weed and crop plants are so dissimilar in growth habits and seed and other characteristics a fair comparison could hardly be made on the basis of seed or straw yields alone. It seemed logical, however, to use the total dry matter from equal areas for such comparisons. Therefore although the amounts of seed and straw were given due consideration in the interpretation of results, only data on the total dry matter were used in the various comparisons.

The results from the competition plots are expressed in percentage. The total dry matter of each crop was taken from one four-foot row. The yield of the weed grown in competition with a crop is expressed as a percentage of the yield of the crop. This shows at once the degree of success or failure of each competitor (see Table I). The results from the single rows and single plants, on the other hand, are presented in absolute weights, which are reliable criteria of growth where competition was not a factor.

TABLE I

RELATIVE COMPETITIVE EFFICIENCY OF WEEDS AND CEREALS AS SHOWN BY DRY MATTER WEIGHTS OF TOP GROWTH EXPRESSED IN PERCENTAGE OF THE CEREAL YIELDS, 1930-1932

| Plants in competition | Hannchen barley (smother crop), % | Prolific spring rye (cleaning crop), % | Marquis wheat (moderate competitor), % | Banner oats (moderate competitor), % | Crown flax (weedy crop), % | Wild oats (weed), % |
|---|---|---|---|---|---|---|
| Cereals | 100 | 100 | 100 | 100 | 100 | 100 |
| Wild oats | 4(2) | 10(2) | 77(2) | 45(4) | 35(2) | – |
| Wild mustard | 4(3) | 39(2) | 43(3) | 94(4) | 443(3) | 286(2) |
| Tumbling mustard | 2(3) | 12(3) | 12(2) | 11(3) | 83(3) | 34(2) |
| Hare's-ear mustard | 1(2) | 8(2) | 7(1) | 13(2) | 386(2) | 24(2) |
| Stinkweed | 12(3) | 3(3) | – | 6(4) | 37(3) | 6(2) |
| Peppergrass | 1(3) | 6(3) | 3(2) | 1(3) | 7(3) | – |
| Lamb's-quarters | 3(3) | 36(2) | 18(3) | 50(4) | 374(3) | 17(2) |
| Redroot pigweed | 3(3) | 21(2) | 19(2) | 84(3) | 442(3) | 28(2) |
| Russian pigweed | – | – | 13(2) | 73(2) | – | 24(2) |
| Russian thistle | – | – | 17(2) | 33(2) | – | 94(2) |
| Blue bur | 0(2) | 1(2) | 3(2) | 8(2) | 85(2) | – |
| Wild buckwheat | 6(2) | 4(2) | 9(2) | – | 421(2) | – |
| Cow cockle | 2(2) | 8(2) | 20(3) | 40(3) | 887(2) | 25(2) |

NOTE.—*All data are averages of material from representative plots grown in one, two or three different years as indicated by the figures in brackets; (4) indicates that in one of the three years the replicates were not uniform enough to be represented by one plot, therefore two plots were used.*

Results on dry matter from competing and non-competing material are shown in Table II. Column 2 shows the dry matter obtained from 4-ft. rows of cereals and from weeds grown between such rows in the competition plots. Column 3 shows the amounts secured from 4-ft. rows of crop and weed plants when rows were widely spaced. In Column 4 appear the amounts from

TABLE II

DRY MATTER FROM TOP GROWTH OF WEED AND CEREAL PLANTS GROWN ALONE AND IN SPACED ROWS IN 1932

| Plant | Amount of air-dry matter (gm.) from | | | |
|---|---|---|---|---|
| | Four-foot rows | | Single plants | |
| | Competing rows 6 in. apart | 5 separate rows 45 in. apart | In competing rows 6 in. apart | Alone on 100 sq. ft. |
| Marquis wheat | 166 | 427 | 4.1 | 28 |
| Reward wheat | 185 | 431 | 4.3 | 26 |
| Reliance wheat | 216 | 508 | 5.1 | 19 |
| Garnet wheat | 150 | 403 | 3.2 | 27 |
| Prolific spring rye | 177 | 389 | 4.2 | 18 |
| Hannchen barley | 186 | 631 | 4.7 | 43 |
| Colsess barley | 176 | 365 | 4.3 | 14 |
| Regal barley | 145 | 594 | 3.7 | 39 |
| Trebi barley | 146 | 649 | 3.8 | 42 |
| Banner oats | 133 | 502 | 3.4 | 33 |
| Gopher oats | 158 | 522 | 3.9 | 35 |
| Wild oats (as crop) | 76 | 738 | 2.0 | 47 |
| Wild oats (as weed) | 44 | | | |
| Crown flax | 41 | 273 | 1.0 | 12 |
| Common wild mustard | 34 | 1223 | 1.1 | 228 |
| Tumbling mustard | 2 | 391 | 0.3 | 137 |
| Hare's-ear mustard | 10 | 732 | 0.25 | 195 |
| Stinkweed | 2 | 411 | 0.03 | 21 |
| Peppergrass | 1 | 202 | 0.01 | 17 |
| Lamb's-quarters | 17 | 1819 | 0.5 | 393 |
| Redroot pigweed | 25 | 1192 | 0.7 | 112 |
| Russian pigweed | 24 | 1406 | 0.6 | 215 |
| Russian thistle | 19 | 2027 | 0.5 | 1662 |
| Blue bur | — | 172 | — | 9 |
| Wild buckwheat | — | 378 | — | 39 |
| Cow cockle | 21 | 1214 | 0.5 | 79 |

NOTE.—*Figures for cereals are averages of ten, and for weeds of four, replicates.*

representative single plants from the competition plots and in Column 5 the amounts from single plants each grown on an area of 100 sq. ft. The data in Column 5 indicate the limits of the natural power of the plant to utilize the environment. This, taken in conjunction with the data in the other columns, gives an idea of the extent of the claims which each species makes upon the environment in competing association. A single striking example of the effects of competition thus illustrated might be quoted here. One plant of Russian thistle growing free from competition produced 1662 gm. of dry matter and hundreds of thousands of seeds, while another, which emerged on the same day but grew in competition with Hannchen barley, produced

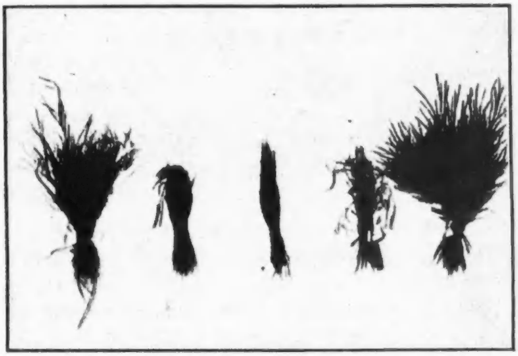


FIG. 2. *Amount of top growth from 4-foot row of hare's-ear mustard grown in competition (from left to right) with (1) Marquis wheat, (2) Prolific spring rye, (3) Banner oats, (4) Hannchen barley, and (5) Crown flax.*

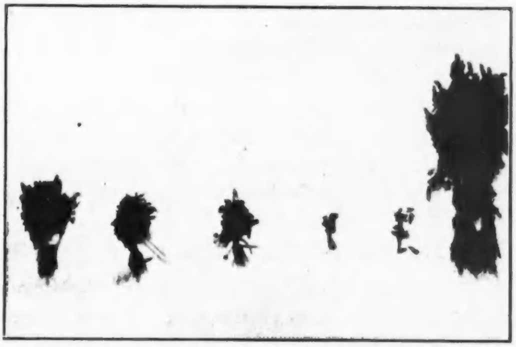


FIG. 3. *Amount of top growth from 4-foot row of redroot pigweed grown in competition (from left to right) with (1) Marquis wheat, (2) Prolific spring rye, (3) Banner oats, (4) Sol barley, (5) Hannchen barley, and (6) Crown flax.*

FIG. 4. *Amount of top growth from 4-foot rows of cow cockle grown in competition (from left to right) with (1) Marquis wheat, (2) Prolific spring rye, (3) Banner oats, (4) Sol barley (early), (5) Hannchen barley, and (6) Crown flax.*

only 0.5 gm. of dry matter and no seeds. The data in Column 4 indicate the extent of the reduction in vigor of the plants due to competition from the surrounding growth. Similar information may be obtained by comparing Columns 2 and 3 which show the yields from competing rows and from widely spaced rows free from interspecific competition.

*Discussion of Results*

Throughout the tests differences in the ability of crops to suppress various weeds have been very consistent. This is illustrated in Figs. 2, 3 and 4, which show the reductions in top growth of weeds as affected by six crop varieties.

It was evident from plot observations that the barleys were the most successful competitors and that Prolific spring rye was next in effectiveness. Marquis wheat and Banner oats followed, neither being consistently superior to the other. Crown flax was always the poorest competitor of the crops used, the weeds in competition with it growing profusely and seriously reducing its yield. On the basis of the top growth only, the crops were classified according to their competitive power as follows:

Smother crops:—Hannchen and Sol barley.
Cleaning crop:—Prolific spring rye.
Moderate competitors:—Banner oats and Marquis wheat.
Very poor competitor:—Crown flax.

The weeds studied were also classified according to their competing ability. Where a sufficient number of data were not available classification was based on general observation. Names of weeds classified on this basis appear in brackets. The classification follows.

Serious weeds:—Common wild mustard *(Brassica arvensis)*, wild oats *(Avena fatua)*, stinkweed *(Thlaspi arvense)*.

Serious under certain conditions or in certain crops:—Redroot pigweed *(Amaranthus retroflexus)*, lamb's-quarters *(Chenopodium album)*, cow cockle *(Vaccaria vulgaris)*, tumbling mustard *(Sisymbrium altissimum)*, hare's-ear mustard *(Conringia orientalis)*, wild buckwheat *(Polygonum convolvulus)*, Russian thistle *(Salsola kali)*, Russian pigweed *(Axyris amarantoides)*.

Rarely serious:—blue bur *(Lappula echinata)*.

Not serious:—wild peppergrass *(Lepidium intermedium)*.

The data in Table I largely substantiate the above classification.

The results presented in Table I prove that crop varieties and weed species differ greatly in competitive ability and also that practically all of the weeds suffered greatly from competition with the crop plants. Information of this type should afford a sound basis for the improvement of cropping practices for weed control.

## II. Study of the Assimilation Surface

The rate of growth results showed in an empirical way the differences in competing ability among the plants, but did not explain them. It was thought that an explanation might be found in a study of the assimilation facilities of the leaf surface. To this end representative specimens from the widely spaced rows described above were selected at five days after emergence and at the blooming stage, and the total leaf area and numbers of stomata per unit area and per plant were determined.

### *Methods*

The total leaf area was obtained as follows. Specimens were hand pulled and immediately submerged in water to prevent wilting. In the laboratory the leaves of each plant were detached without removing the stem from the water. The entire foliage of each specimen was then withdrawn from the water, hastily mounted over the glass of a blueprint flame, and dried with blotting paper. Blue prints were made immediately. These were cut out and each set of clippings representing the foliage of one plant was weighed. The weights thus obtained were compared with the weight of 100 sq. cm. of blueprint paper. The total leaf area of each specimen was estimated from the formula

$$\frac{Tw \times 100}{cw} = \text{Total leaf area}$$

where $Tw$ is the weight of a set of clippings and $cw$ is the weight of 100 sq. cm. of blueprint paper.

The figure thus obtained indicated the total assimilation surface for plants with stomata on only one surface of the leaf. In cases where stomata occurred on both sides of the leaves the figure was doubled.

In determining numbers of stomata per unit of leaf area and per plant, camera lucida drawings were made. Ten equal microscopical fields were examined from upper and from lower leaf surfaces in each case. The average numbers of stomata thereon were used as a basis for further estimates. To obtain the average number of stomata the total number was divided by 20 where stomata were present on both leaf surfaces and by 10 where they occurred on only one surface. The numbers of stomata per unit of area vary greatly with the age of the leaf and its position on the plant. Average well-developed leaves were used in all cases in this work.

*Discussion of Assimilation Surface Results*

Table III includes the data on total assimilation surfaces and on number of stomata of several weeds and grain plants. The data in Column 2 show that wheat with 8.6 sq. cm. at five days after emergence has the least assimilation surface of the four cereal crops studied. Nevertheless this is greater by 5.8 sq. cm. than the greatest assimilation surface among the dicotyledonous weeds studied, that of cow cockle. This would appear to indicate that the

TABLE III

TOTAL ASSIMILATION SURFACE OF WEED AND CEREAL CROP PLANTS FIVE DAYS AFTER EMERGENCE AND AT BLOOMING, 1930

| Plants | Five days after emergence | | | At blooming | | |
|---|---|---|---|---|---|---|
| | Total assimilation surface, sq. cm. | No. of stomata | | Total assimilation surface, sq. cm. | No. of stomata | |
| | | Per sq. cm.* | Per plant | | Per sq. cm.* | Per plant millions |
| Common wild mustard | 2.5 | 31800 | 79800 | 7300 | 66500 | 490 |
| Tumbling mustard | — | — | — | 2700 | 19300 | 52 |
| Hare's-ear mustard | 1.1 | 20900 | 23000 | 650 | 18700 | 8 |
| Lamb's-quarters | — | — | — | 5700 | 12200 | 69 |
| Redroot pigweed | .7 | 13600 | 9600 | 1400 | 29900 | 42 |
| Russian pigweed | .5 | 4500 | 2300 | 3600 | 20900 | 74 |
| Wild sunflower | — | — | — | 7600 | 74300 | 560 |
| Cow cockle | 2.8 | 13600 | 39200 | 2400 | — | — |
| Wild buckwheat | — | — | — | 2800 | — | — |
| Marquis wheat | 8.6 | 4700 | 40300 | 140 | 4900 | .7 |
| Hannchen barley | 18.6 | 3500 | 64300 | 300 | 4100 | 1.2 |
| Banner oats | 10.2 | 4200 | 43200 | 140 | 4400 | .6 |
| Prolific spring rye | 13.1 | 4900 | 63700 | 150 | 4700 | .7 |
| Wild oats | 6.4 | 4700 | 30300 | 260 | 4800 | 1.2 |

**The assimilation surface of weeds at this stage is mostly the surface of cotyledons which generally possess less stomata per unit area than normal leaves. This is why in a few cases there are large differences between these data and those given in column 6.*

cereals at this stage are more favorably equipped for assimilation activity than the weeds. But assimilation surface is not the sole indicator of the assimilating ability of a plant. The number of stomata per unit of area is also important. Common wild mustard, which has only 2.5 sq. cm. of assimilation surface as compared with the 8.6 of Marquis wheat, has an average of 31,850 stomata per sq. cm., while Marquis wheat has 4,686.

Since the primary purpose of stomata is to facilitate such physiological activities as transpiration and photosynthesis, it is obvious that these functions are more intense in wild mustard than in Marquis wheat despite the larger assimilation surface of the latter. Undoubtedly the extreme troublesomeness of wild mustard in wheat fields is attributable, at least in part, to this factor. It should be emphasized that any advantage one plant may have over another at this early stage of growth is of extreme importance in the final outcome of competition between them. Fortunately all our cereals, in spite of low stomatal numbers per unit of area, have such large assimilation surfaces at early growth stages that they possess greater numbers of stomata per plant at five days after emergence than any of the dicotyledonous weeds studied, except wild mustard. Thus they are able to develop rapidly their tops and roots and to take more or less complete possession of an area before the weeds attain sufficient development to compete seriously with them. This would account to a large extent for the results presented in Tables I and II.

The data given in Columns 5, 6 and 7 of Table III, on the other hand, show clearly that at the blooming stage all of the weeds possess much larger assimilation surfaces and many more stomata than do the cereals. Therefore a crop which fails to smother the weeds at the early stage cannot do it later. It appears that the noxious characteristics of weeds and the competitive efficiency of cereals are dependent to a large extent on the local assimilation surface and the number of stomata per plant and that, because of the quantitative expression of these characters, the cereals are best fitted to compete with the weeds when both are in the early stages of growth.

## III. Readiness and Uniformity of Germination of Weed and Cereal Crop Seeds in Relation to Their Competitive Efficiency

During the years 1930, 1931 and 1932 from 29 to 34 annual weeds and five cereals have been grown side by side in rows. Plantings were made in early spring and approximately every 15 days throughout the growing season in order that the readiness and uniformity of germination of different seeds under different climatic conditions might be observed. In addition, tests were conducted in greenhouse soil boxes, with soil moisture at the optimum for germination and temperature close to 65° F. Readiness of germination is indicated by the number of days from seeding to first emergence, and uniformity by the number of days required by a sample to reach its total germination. Results are shown in Tables IV and V.

TABLE IV

READINESS AND UNIFORMITY OF GERMINATION OF WEED AND CEREAL CROP SEEDS

| Plant | Moisture abundant | | | Moisture scarce | | |
|---|---|---|---|---|---|---|
| | No. of days from seed. to first emergence | No. of days from first germination to total | Total germination, % | No. of days from seed. to first emergence | No. of days from first germination to total | Total germination, % |
| Wild oats | 8 | 14 | 80 | 19 | 22 | 10 |
| Common wild mustard | 4 | 14 | 21 | 11 | 18 | 20 |
| Stinkweed | 8 | 17 | 80 | 15 | 20 | 25 |
| Tumbling mustard | 5 | 14 | 50 | 12 | 19 | 63 |
| Common false flax | 4 | 10 | 28 | 10 | 15 | 25 |
| Lamb's-quarters | 5 | 14 | 80 | 11 | 21 | 24 |
| Russian thistle | 4 | 9 | 90 | 10 | 9 | 29 |
| Cow cockle | 7 | 13 | 85 | 7 | 14 | 28 |
| Wild buckwheat | 8 | 17 | 30 | 17 | 23 | 39 |
| Blue bur | 6 | 14 | 50 | 11 | 18 | 4 |
| Hannchen barley | 5 | 2 | 95 | 6 | 4 | 86 |
| Prolific spring rye | 5 | 3 | 95 | 7 | 3 | 76 |
| Marquis wheat | 5 | 4 | 90 | 7 | 4 | 69 |
| Banner oats | 5 | 2 | 95 | 7 | 3 | 58 |
| Crown flax | 6 | 4 | 43 | 6 | 5 | 32 |

*Each number is the average of 1930, 1931 and 1932 results. In each year there were from four to seven replicates.*

TABLE V

READINESS AND UNIFORMITY OF GERMINATION OF WEED AND CEREAL CROP SEEDS UNDER GREENHOUSE CONDITIONS IN 1932

| Plant | No. of days from seeding to emergence | No. of days from first germination to total | Total germination, % | Plant | No. of days from seeding to emergence | No. of days from first germination to total | Total germination, % |
|---|---|---|---|---|---|---|---|
| Wild oats | 4 | 7 | 74 | Wild buckwheat | 6 | 6 | 11 |
| Common wild mustard | 3 | 8 | 33 | Blue bur | 5 | 7 | 53 |
| Stinkweed | 5.5 | 6 | 10 | Hannchen barley | 3.5 | 2 | 98 |
| Tumbling mustard | 3 | 8 | 69 | Prolific spring rye | 3 | 3 | 84 |
| Common false flax | 3 | 8 | 1 | Marquis wheat | 3.5 | 3.5 | 100 |
| Lamb's-quarters | 4 | 8 | 32 | Banner oats | 3.5 | 2 | 98 |
| Russian thistle | 2 | 9 | 2 | Crown flax | 3 | 3 | 41 |
| Cow cockle | 5 | 6 | 61 | | | | |

NOTE.—*Duplicate 100-seed tests under optimum moisture conditions were made in each case.*

### *Discussion*

This study showed that the plants concerned could be grouped into two more or less distinct classes on the basis of readiness and uniformity of germination. Seeds of the first class, which included roughly all of the weed species, showed a low capacity to germinate when soil moisture was scarce.

The cereals however exhibited marked ability to use even very small amounts of soil moisture for germination. This fact is of much importance for it indicates that the small grains have a distinct advantage in competition with weeds when the soil is low in moisture content at seeding time.

When soil moisture was more plentiful nearly all of the weeds of the mustard family and most of the pigweeds and cockles germinated as readily as the cereals but never so uniformly. It was only under conditions of extreme drought, or after seeding poorly done, that good seed of the grain crops germinated unevenly. Otherwise, as shown in Tables IV and V a good stand was established within two or three days after the first plants had emerged. Weed seeds, as the same tables show, usually germinated very unevenly.

## IV. Root Study of Weed and Cereal Crops in Relation to Their Competitive Efficiency

The greater ability of cereal crop seeds to germinate in the presence of but slight amounts of soil moisture, and the rapid growth of the plants with the production of large assimilation surfaces in the early stages, are important factors in the competition of cereals with weeds. The root system is the third and perhaps the most important factor. Growth appears above the surface only after the plant has established itself in the soil. It would, therefore, appear that the future well-being of the plant might depend largely on the early development of its root system. The importance of detailed knowledge of the root systems of plants in relation to their competitive reactions can hardly be overemphasized, consequently much emphasis has been placed on root investigation in this study.

The work of three years has shown that the root systems of the weeds and crops differ markedly in growth habit, extent, distribution and penetration. These differences help to explain why some crops grown in weedy districts are relatively clean while others, in areas otherwise relatively weed-free, are badly infested. They also explain why some weeds, although prevalent, never do much harm to crops while others become a menace soon after they invade a district. The results are presented in Tables VI to IX.

The primary purpose of the work was to obtain basic information for an attack on practical weed problems but details of only theoretical interest were not overlooked. The major objective was the determination of the quantitative distribution of the roots in the working areas. For this purpose diagrams indicating the tendency of distribution of roots are not enough; the quantity actually present must be determined. No attempt was made to obtain material by excavation. Blocks of soil large enough to include the root system or at least its complete working sphere were removed and the root material was extricated by washing from the bottom upwards with a fine spray of water from the nozzle of a garden hose. The soil was removed in such fine particles that usually not even the smallest rootlets were appreciably damaged. As the work proceeded the position of primary and secondary roots, and the depth and lateral spread of the main mass of fine rootlets were

recorded on graph paper. The root systems were finally submerged in water and measured. They were then spread, in accordance with the graphical records, dried and photographed. Data presented respecting plants 5 and 21 days old are averages obtained from 5 to 10 individual plants but data on mature plants represent only one or two specimens.

A study was made of the correlation between the mass, length, spread and position of the roots and the rates of growth of the plants. On this basis the weeds and crops were classified as noted in the rate of growth study and in Table VI.

TABLE VI

COMPARATIVE STUDY OF THE ROOT SYSTEMS OF ANNUAL WEEDS AND CEREAL CROPS 5 AND 21 DAYS AFTER EMERGENCE

| Weeds | Length in inches | | Crops | Length in inches | |
|---|---|---|---|---|---|
| | 5 days after emergence | 21 days after emergence | | 5 days after emergence | 21 days after emergence |
| Wild oats (serious weed) | 34.7 | 952.9 | Hannchen barley (smother crop) | 174.5 | 2286† |
| Common wild mustard (serious weed) | 34.7 | 4747 | Trebi barley (smother crop) | 67.5 | 3974 |
| Stinkweed (serious weed) | 17.5 | 3935 | Regal barley (smother crop) | 110.1 | — |
| Lamb's-quarters (serious weed in certain crops and under certain conditions) | 5.8 | 3251 | Prolific spring rye (cleaning crop) | 115.2 | 2127† |
| Cow cockle (sometimes serious weed) | 27.8 | 1626† | Colsess barley (cleaning crop) | 95.5 | — |
| Hare's-ear mustard (occasionally serious weed) | 12.8 | 1491 | Marquis wheat (moderate competitor) | 118.5 | 3047 |
| Redroot pigweed (serious weed in certain crops) | 9.0 | 390.6† | Reward wheat (moderate competitor) | 82.6 | 2550 |
| Russian pigweed (serious weed under certain conditions) | 5.1 | 348.6† | Garnet wheat (more than moderate competitor) | 100.8 | 2773 |
| Tumbling mustard (serious weed in thin stands of grain crops) | 7.8 | 339.8 | Reliance wheat (moderate competitor) | 98.8 | 1953 |
| | | | Gopher oats (more than moderate competitor) | 38.1 | 1367 |
| | | | Banner oats (moderate competitor) | 95.2 | 875 |

†*Great care was exercised to procure the complete root system of each plant, if possible. Cases where some minor loss occurred are marked †.*

NOTE.—*All data are averages from five replicates.*

An illustration of the type of material studied is shown in Fig. 11. This single secondary root of Trebi barley with its side branches was separated from the root system at maturity. The branches of this specimen were measured and counted. There were 7,870 branches with a total length of 6,778 in. The accuracy and efficiency of the technique used is demonstrated by the fact that many branches of the first order measuring up to 28 in. still bore their root caps.

*Results and Discussion*

Table VI includes comparative data for nine annual weeds and eleven standard varieties of cereals. It will be noted that at five days after emergence the root systems of the two most serious weeds, wild oats and common wild mustard, measured only 34.5 linear in. The smallest root system among the cereal crops at this stage measured 38.1 in. Reference to Table III will show that these weeds also had a smaller assimilation surface at the same stage. These facts indicate that there is a high correlation between underground developments and top growth and that the cereals excel the weeds in both these characters at the five-day stage.

A second notable point in Table VI is that at 21 days after emergence common wild mustard produced the greatest root system of any plant studied. It was closely followed by stinkweed, another noxious species. The rest of the weeds fall in approximately the same positions as they were found to occupy in the rate of growth study.

It is apparent that most noxious weeds at 21 days after emergence have greater root systems and greater assimilation surfaces than any of the cereals studied and that consequently no cereal crop can compete successfully with them after this stage of development. It also appears to be true that the noxious characters of weeds are more closely correlated with root development than are the competitive faculties of the cereals. This point will be discussed later.

The relative development of the root systems of weed and crop plants is illustrated in Figs. 5, 6, 7 and 8.

In Table VII root systems of 10 representative plants are analyzed with respect to their numbers of primary and secondary roots and their penetration and distribution in 1931. Hannchen barley had the largest number of

TABLE VII

ANALYSIS OF THE ROOT SYSTEMS OF WILD OATS AND CEREAL CROPS WITH RESPECT TO AVERAGE NUMBER OF PRIMARY AND SECONDARY ROOTS AND THEIR PENETRATION AND DISTRIBUTION IN 1931

| Plants | Averages from ten replicates | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Number of roots per plant | | Per cent of roots penetrating deeper than | | | | | | Length of greatest feeders of the 1st order, in. |
| | | | 18 in. | 24 in. | 27 in. | 18 in. | 24 in. | 27 in. | |
| | Primary | Secondary | Primary | | | Secondary | | | |
| Hannchen barley (smother crop) | 7 to 10 | 7 to 17 | 80 | 60 | 50 | 20 | 15 | 10 | 13+ |
| Prolific spring rye (cleaning crop) | 4 to 5 | 8 to 14 | 55 | 45 | 35 | 20 | 10 | 5 | 11.5+ |
| Marquis wheat (moderate competitor) | 4 | 6 to 18 | 85 | 75 | 65 | 60 | 55 | 50 | 18+ |
| Banner oats (moderate competitor) | 3 (rarely 4) | 8 to 15 | 80 | 70 | 60 | 50 | 30 | 10 | 16+ |
| Wild oats (weed) | 3 | 7 to 25 | 96 | 80 | 75 | 60 | 40 | 25 | 22+ |

PLATE I

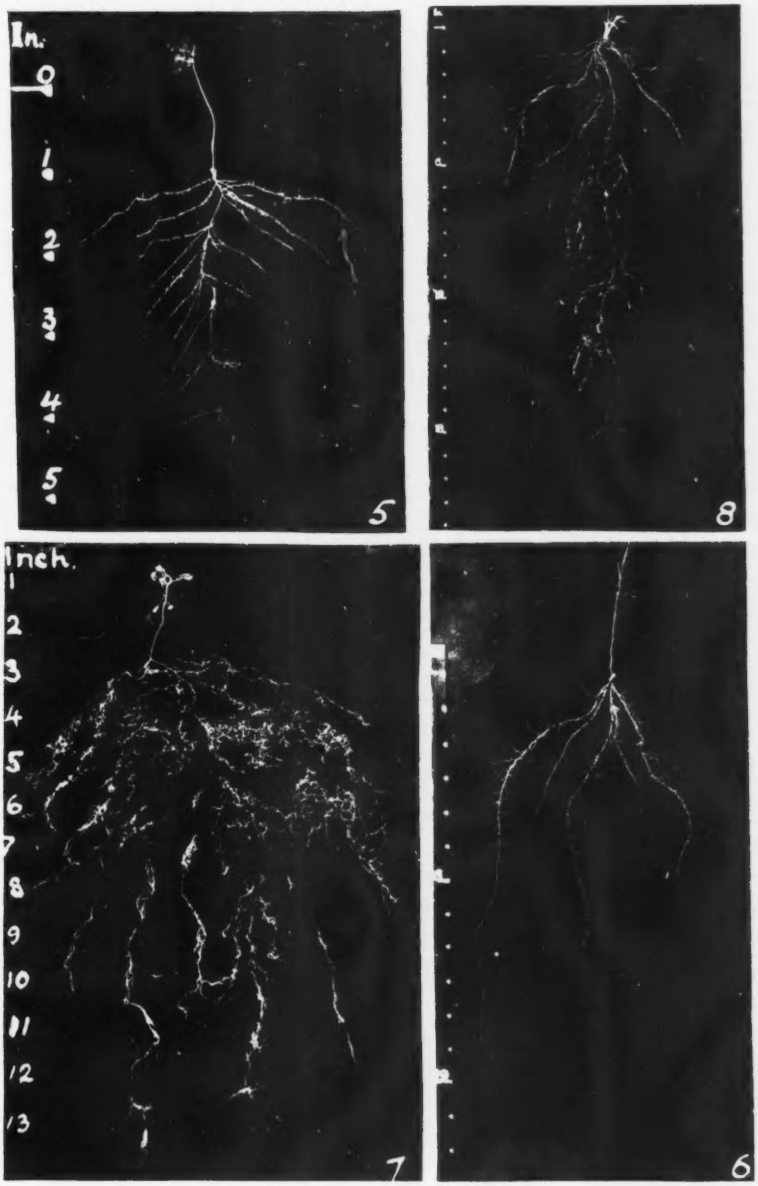



FIG. 5. *A complete root system of common wild mustard at 5 days after emergence, penetrating to a depth of 5 in. and measuring 34.7 in.* FIG. 6. *A complete root system of Garnet wheat at 5 days after emergence, penetrating to a depth of 12 in. and measuring 100.8 in.* FIG. 7. *A complete root system of common wild mustard at 21 days after emergence, penetrating to a depth of 13.4 in. and measuring 4,747 in.* FIG. 8. *A complete root system of Garnet wheat at 21 days after emergence, penetrating to a depth of 24 in. and measuring 2,773 in.*

primary roots per plant. Prolific spring rye, Marquis wheat, Banner oats and wild oats followed in order. Prolific spring rye had the greatest concentration of primary and secondary roots comparatively close to the surface. Hannchen barley resembled Prolific spring rye most closely in this respect and was followed by Banner oats, Marquis wheat and wild oats. Most of the primary and many of the secondary roots of Banner oats, Marquis wheat and, in particular, wild oats attained much greater depths than did those of Hannchen barley and Prolific spring rye.

The differences just described are important since it seems that the competitive efficiency of each plant, and especially of the cereals, is defined not only by the extent of the root system but by the natural distribution of the roots. For example, under favorable circumstances wheat varieties may develop root systems as great or greater than those of barley (see Table VI). But as these roots are more or less evenly and thinly distributed to a considerable depth (Table VII), wheats are not so successful as competitors with weeds as are rye and barley, the root systems of which are concentrated close to the surface.

Table VIII provides further evidence of close correlation between competing efficiency and development of root systems. Hannchen barley, a smother crop, possessed the greatest root system of the four cereals at all three stages but was excelled at maturity by wild oats. The other cereals followed in the order of their competitive efficiency in the first two stages, but at maturity Prolific spring rye showed divergence from expectation. This may be explained by the fact that the exceedingly fine rootlets of this crop

TABLE VIII

COMPARATIVE LENGTHS OF THE ROOT SYSTEMS OF WILD OATS AND CEREAL CROPS AT THREE DIFFERENT STAGES,* 1931

| Plant (ten replicates) | Age, days from emergence | Number of roots per plant, primary | Total average length per plant, in. | Ratio between* 5, 22 and 80 day developments |
|---|---|---|---|---|
| Hannchen barley | 5 | 6.5 | 45.7 | |
| (smother crop) | 22 | 7.6 | 1245.3 | 3.2 : 89 : 612 |
| | 80 | 8.5 | 8565.0 | |
| Prolific spring rye | 5 | 4.5 | 19.1 | |
| (cleaning crop) | 22 | 5.3 | 682.7 | 1.3 : 49 : 196 |
| | 80 | 5.3 | 2748.0 | |
| Marquis wheat | 5 | 3.6 | 17.7 | |
| (moderate competitor) | 22 | 4.2 | 649.1 | 1.3 : 46 : 440 |
| | 80 | 4.0 | 6160.0 | |
| Banner oats | 5 | 3.1 | 17.88 | |
| (moderate competitor) | 22 | 3.6 | 646.6 | 1.3 : 46 : 468 |
| | 80 | 3.5 | 6552.0 | |
| Wild oats | 5 | 3.0 | 13.93 | |
| (weed) | 22 | 3.0 | 273.0 | 1.0 : 20 : 721 |
| | 80 | 3.0 | 10100.4 | |

**The root system of wild oats five days after emergence is used as a unit for these values.*

break off easily and many may have been lost in washing out the material. Having only three primary roots wild oats started with a smaller root system than any of the cereals and this system increased very slowly at first. Later it developed many more secondary roots than the cereals and at maturity the root system of wild oats excelled that of Hannchen barley.

A good picture of the relative development of the root systems of some crop plants and wild oats is presented in Table IX and Figs. 12, 13, 14, 15 and 16. Table IX shows the lengths and weights and the figures illustrate the distribution of the root systems.

TABLE IX

RELATIVE WEIGHTS AND LENGTHS OF ROOT MATERIAL OF MATURE PLANTS WITHIN BLOCKS OF SOIL 12 BY 12 BY 27 IN. (ORDINARY DRILL ROW PLOTS), IN 1931.

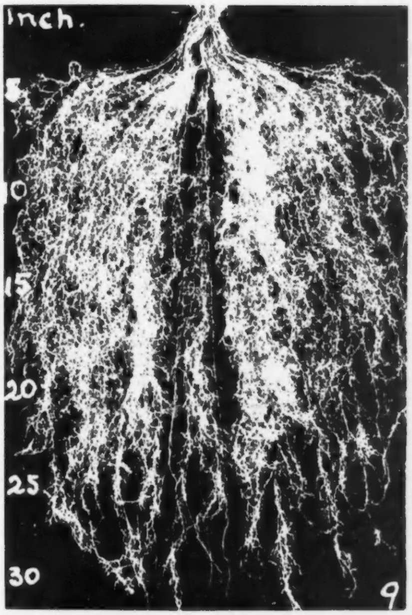
| Plants | Air dry material from one-foot row | |
|---|---|---|
| | Weights, gm. | Lengths, ft. |
| Hannchen barley (smother crop) | 17.837 | 20,202 |
| Prolific spring rye (cleaning crop) | 7.123 | 7,783* |
| Marquis wheat (moderate competitor) | 7.181 | 10,783 |
| Banner oats (moderate competitor) | 6.017 | 5,460 |
| Wild oats (weed) | 15.189 | 20,203 |

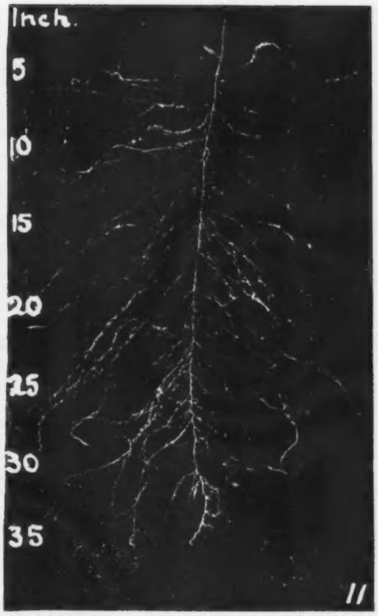
**Rye suffered a heavy loss of fine fibre at the time of washing.*

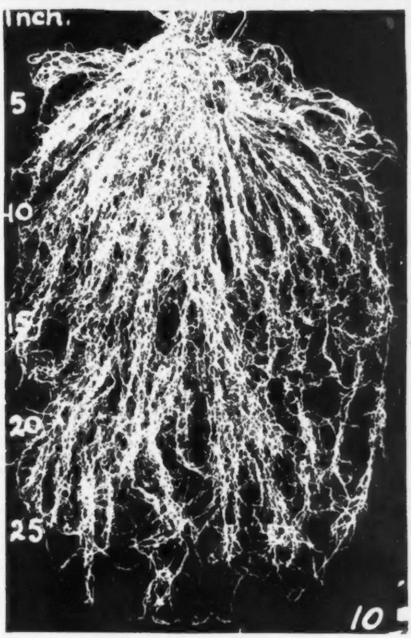
Fig. 12 shows the concentration of the great mass of root fibre of Hannchen barley in the upper 10 in. of soil. This thorough occupation of the upper stratum leaves little available moisture for weed plants. Some of the primary roots penetrated more deeply in search of moisture but these never went as deep as the roots of rye, oats, or wheat, a fact which may explain the comparative sensitiveness of barley to drought.

Prolific spring rye (Fig. 13) developed less root material per unit volume of soil than did barley, but a proportionately greater amount of it was located immediately below the surface. Very few of its primary, and still fewer of its secondary, roots penetrated to great depths to supply moisture in periods of low precipitation. It is obvious that its competing efficiency is due more to the distribution than to the size of the root system.

In the case of Marquis wheat (Fig. 14) the major part of the root mass is found at a considerable distance from the surface. In the first seven inches there was a fair amount of fine fibre but in the next layer of nine inches there was only a thin network of sparsely branched primary and secondary roots. At still greater depths there was profuse branching of primary and particularly of secondary roots resulting in a denser mass of feeders than was found in the upper strata. Many of the secondary, and even more of the primary roots reached depths of several feet. This type of root system is better adapted for drought resistance than for competition with weeds. While it may account for the suitability of Marquis wheat to the drier zones, it also allows weeds a favorable opportunity to become established because of the scarcity of wheat roots in the upper levels.



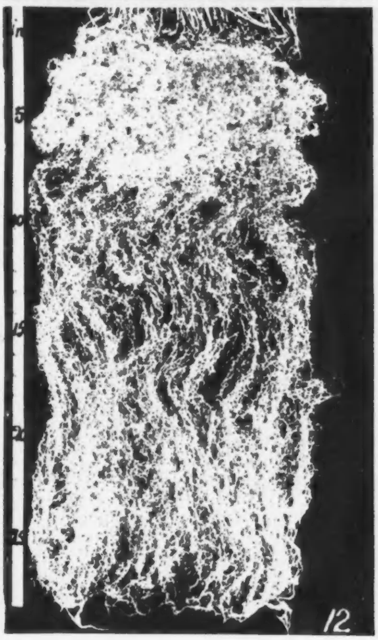




FIG. 9. *Root system of Trebi barley single plant at maturity washed out from a block of soil 26 by 26 by 42 in.* FIG. 10. *Root system of wild oat single plant measuring 7,987 ft.* FIG. 11. *A single secondary root of Trebi barley with its 7,870 branches of 1st, 2nd, and 3rd orders measuring 6,778 in.* FIG. 12. *Root material from one foot of ordinary drill row of Hannchen barley (smother crop) weighing 17.837 gm. and measuring 20,202 ft. (Air-dry material.)*

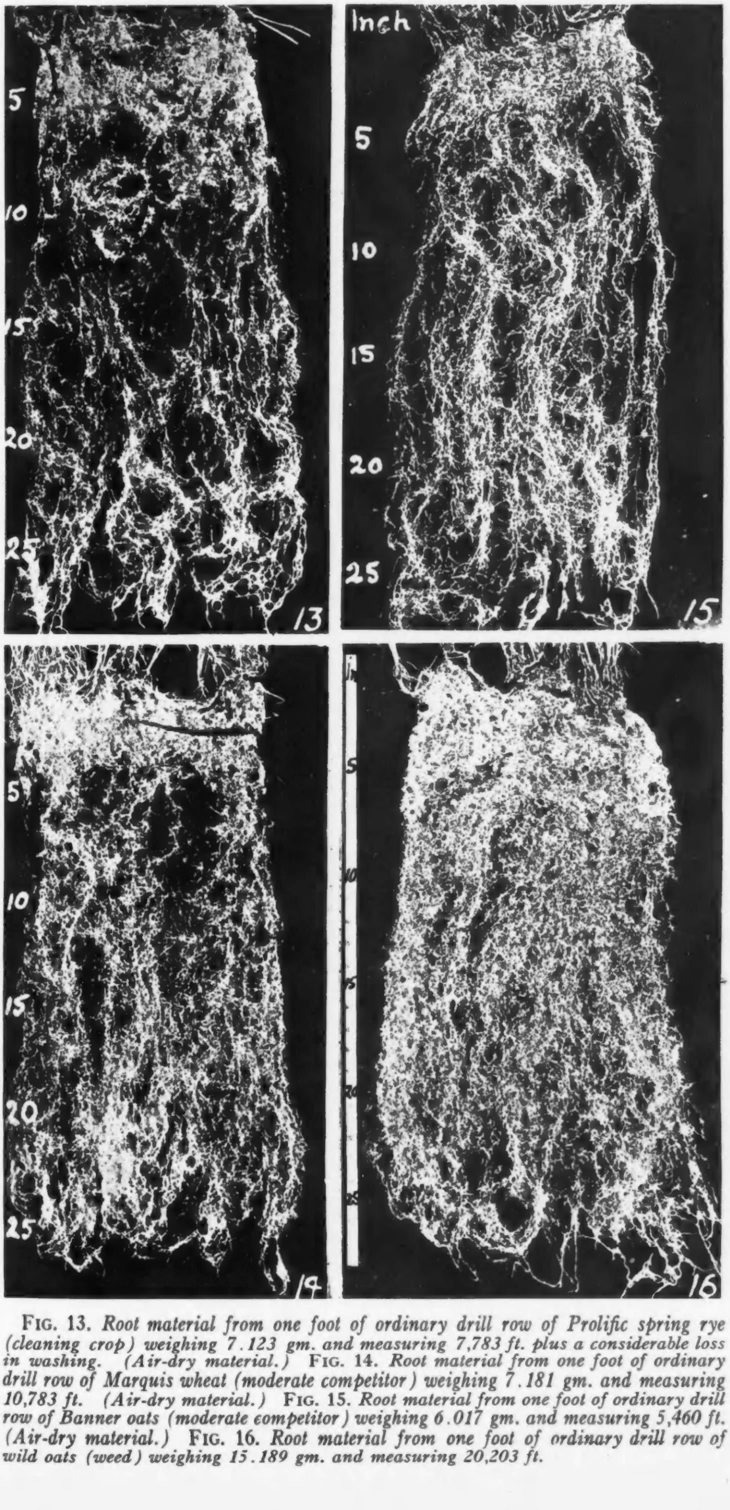



FIG. 13. *Root material from one foot of ordinary drill row of Prolific spring rye (cleaning crop) weighing 7.123 gm. and measuring 7,783 ft. plus a considerable loss in washing. (Air-dry material.)* FIG. 14. *Root material from one foot of ordinary drill row of Marquis wheat (moderate competitor) weighing 7.181 gm. and measuring 10,783 ft. (Air-dry material.)* FIG. 15. *Root material from one foot of ordinary drill row of Banner oats (moderate competitor) weighing 6.017 gm. and measuring 5,460 ft. (Air-dry material.)* FIG. 16. *Root material from one foot of ordinary drill row of wild oats (weed) weighing 15.189 gm. and measuring 20,203 ft.*

The root system of Banner oats (Fig. 15) resembles that of Marquis wheat. This may account for their interchanges of position in the competition studies. Banner oats however has slightly more fibre in the upper levels and a more even distribution throughout the occupied depth.

Wild oats (Fig. 16) produced more root material than any of the cereals studied. From the surface to great depths its roots occupied the soil almost completely. Its primary and secondary roots branched and rebranched producing near the surface a dense network which evenly and very gradually diminished with increasing depth. Many side branches of primary and secondary roots were 22 in. or more in length. That cereals are able to compete at all with this weed may be explained first by the slower normal germination of the wild oat and secondly by the fact that the wild oat has not more than three primary roots and develops its root system very slowly at early growth stages.

The mature root systems of Trebi barley and wild oats illustrated in Figs. 9 and 10 provide a basis for comparison of an effective smother crop with a very noxious weed. The total length of the wild oat roots was 7,987 feet and that of the Trebi barley almost as much. A Hannchen barley root system measured 6,917 feet. Such root development evidently accounts both for the effectiveness of barley as a smother crop and for the noxious character of wild oats.

## Acknowledgment

The writers wish to acknowledge their appreciation of the time and effort expended on this work by Dr. L. E. Kirk, Dominion Agrostologist, Central Experimental Farm, Ottawa, during 1930 and 1931, when he was in charge of the weed research at the University of Saskatchewan.

## References

1. AALTONEN, V. T. Ueber die räumliche Ordnung der Pflanzen auf dem Felde und im Walde. Act. For. Fenn. 23 : 7-85. 1923.
2. BARNES, S. and HOPKINS, E. S. Soil moisture and crop production. Dom. Dept. of Agric. Bull. 130 n.s. 27-30. 1930.
3. BRENCHLEY, W. E. Weeds of farm land. Longmans, Green and Co., London. 159-174. 1920.
4. CLEMENTS, F. E. Development and structure of vegetation. Rept. Bot. Surv. Nebr. 7 : 5-175. 1904.
5. CLEMENTS, F. E. Research methods in ecology. 1905.
6. CLEMENTS, F. E. and WEAVER, J. E. Experimental vegetation. Carnegie Inst. Wash. Pub. 355. 1924.
7. CLEMENTS, F. E., WEAVER, J. E. and HANSON, H. C. The nature and role of competition. Carnegie Inst. Wash. Year Book 23 : 252-255. 1924.
8. CLEMENTS, F. E., WEAVER, J. E. and HANSON, H. C. Plant competition. Carnegie Inst. Wash. 1929.
9. DE CANDOLLE, A. P. Essaie élémentaire de géographie botanique. 26-28. 1920.
10. DE CRESCENTIIS, PETRUS. Handschrift. 1305.
11. HANSON, A. A. When alfalfa beats the weeds. Successful farming. Meredith Pub. Co. March. 1931.
12. HANSON, H. C. The struggle for existence among range plants. The Producer. Denver, Col. 11 (4) : 5-7. 1929.
13. HOPKINS, E. S. Report of the Dominion Field Husbandman, Ottawa. 37. 1926.

14. Hopkins, E. S. Report of the Dominion Field Husbandman, Ottawa. 34-35. 1927.
15. Hopkins, E. S. Report of the Dominion Field Husbandman, Ottawa. 43-46. 1928.
16. Hopkins, E. S. Report of the Dominion Field Husbandman, Ottawa. 57-59. 1929.
17. Hopkins, E. S. Report of the Dominion Field Husbandman, Ottawa. 43-44. 1930.
18. Hopper, W. C. Crops that aid in subduing weeds. Canadian Countryman, 19 : 19. Toronto. 1930.
19. Kiesselbach, T. A. Studies concerning the elimination of experimental error in comparative crop tests. Neb. Agr. Exp. Sta. Res. Bull. 13. 1918.
20. Montgomery, E. G. Competition in cereals. Neb. Agr. Exp. Sta. Bull. 113. 1912.
21. Nägeli, C. 1874. Verdrängung der Pflanzenformen durch ihre Mitbewerber. Sitzb. Akad. Wiss. München, 11 : 109-164. Bot. Mitt. 3 : 205-260. 1881.
22. Sukatschew, W. Einige experimentelle Untersuchungen über den Kampf ums Dasein zwischen Biotypen derselben Art. Zeits. Indukt. Abs. Vererb. 47 : 54-74. 1927.

# STUDIES ON FOOT AND ROOT ROT OF WHEAT

## III. EFFECT OF CROP ROTATION AND CULTURAL PRACTICE ON THE DEVELOPMENT OF FOOT ROT OF WHEAT[1]

By W. C. Broadfoot[2]


## Abstract

The following conclusions are drawn from a uniform, co-operative, crop sequence study at seven stations in western Canada, *viz.*, Morden, Indian Head, Swift Current, Scott, Lethbridge, Olds and Vermilion, from 1928 to 1932, inclusive (a total of 28 station-years). Foot-rot damage of wheat is significantly reduced where wheat alternates with summerfallow in a two-year rotation, where it follows summerfallow in other rotations, alternates with oats in a two-year rotation, follows oats in a three-year rotation, follows sweet clover in a three-year rotation, or where wheat is sown late. It is increased where wheat follows wheat, barley, or western rye grass.


## Introduction

The loss to the wheat crop in western Canada from that complex, commonly referred to as foot and root rot, is very important. Often it is attributed to one or more of the following organisms:—*Ophiobolus graminis* Sacc., *Helminthosporium sativum* P. K. and B., *Fusarium* spp., *Leptosphaeria herpotrichoides* de Not., *Wojnowicia graminis* (McAlp.) Sacc. and D. Sacc., and *Pythium* spp. Perhaps only in exceptional cases does one of the fungi mentioned cause all the damage observed. *H. sativum* and several *Fusarium* spp. are constantly associated with foot-rot damage, even when either may not be the principal agent. Some estimates of the loss from the various foot rots in several countries are listed in Table I. As a group these diseases are particularly prevalent and severe in western Canada in favorable seasons, and they are prevalent each year. Undoubtedly the foot rots in Alberta cause a much greater reduction in yield of wheat any season, than do the smuts and the rusts combined.

It was first pointed out by Sanford (53) that the conditions in the black soils of Alberta appeared to be particularly favorable to take-all, and the conditions in the non-black soils distinctly less so. The foot rots caused by *H. sativum* and *Fusarium* spp. develop readily, both in the black and non-black soils of Alberta, Saskatchewan and Manitoba. Moreover, the evidence is that the damage does not diminish, but rather increases with the crop methods used. Bolley (6) attributed part of the increasing unproductiveness of land in North Dakota to the presence of foot-rotting organisms, which

[1] *Manuscript received October 4, 1933.*
*Contribution from the Division of Botany, Experimental Farms Branch, Department of Agriculture, Ottawa, Canada, co-operating with the Dominion Experimental Farms at Morden in Manitoba, Indian Head, Swift Current and Scott in Saskatchewan, and at Lethbridge in Alberta, and the Alberta Schools of Agriculture at Olds and Vermilion. This paper constitutes one part of a thesis submitted May 3, 1932, to the graduate faculty of the University of Minnesota in partial fulfilment of the requirements for the degree of Doctor of Philosophy. Read at Regina meetings of the Canadian Phytopathological Society, July, 1933. Abstract appears in Proceedings, World's Grain Show and Conference, Ottawa, 1933.*
[2] *Plant Pathologist, Dominion Laboratory of Plant Pathology, Edmonton, Alberta.*

TABLE I

ESTIMATED LOSS OF THE WHEAT CROP DUE TO VARIOUS FOOT-ROTTING ORGANISMS IN CERTAIN AREAS

| Authority | Year | Region | Primary causal organism | Estimated loss |
|---|---|---|---|---|
| Atanasoff (4) | 1920 | U.S.A. | *Gibberella saubinetii* | 20,000,000 bushels annually. Causes seedling blight as well |
| Stakman (59) | 1919 | Minn. | *Helminthosporium sativum* | 1 to 50% in individual fields |
| Heald (26) | 1923 | Wash. | Foot rot complex | 40% of 4,000 acres in Spokane Valley. 30-50% reduction in yield |
| Christensen (10) | 1922 | Minn. | *Helminthosporium sativum* | 10-20% in Dakota, McLeod and Rice counties |
| Johnson and Dickson (30) | 1919 | U.S.A. | *Gibberella saubinetii* | 80,000,000 bushels in 1919 |
| Christensen and Stakman (11) | 1925 | Minn. | Foot rot complex | 2-4% of common wheats, 5 to 15% of durum,— as high as 75% in individual fields |
| MacKinnon (34) | 1920 | Australia | *Ophiobolus graminis* | 12-15% of Australian crop in certain years, with an average reduction for all years of 7% |
| Stakman (60) | 1921 | Oregon | *Ophiobolus graminis* | ¼ of wheat crop was lost at Hillsboro |
| Anon. (2) | 1922 | Oregon | *Ophiobolus graminis* | Considerable number of fields not worth threshing |
| Kirby (32) | 1925 | New York | *Ophiobolus graminis* | 0.3 to 2% loss, although losses as high as 20% were observed in individual fields |
| Sanford (51) | 1925 | Sask. | *Ophiobolus graminis* | Varied from slight to 15-20% loss in individual fields |
| Russell (46) | 1927 | W. Canada | *Ophiobolus graminis* | 15-20% loss in individual fields |
| Sanford (53) | 1927 | Alta. | *Ophiobolus graminis* | 7,000,000 bushels for Alberta only |
| Sanford (54) | 1928 | Alta. | *Ophiobolus graminis* | Loss in 30% of 914 fields examined —very significant |
| Russell (47) | 1928 | Sask. | *Ophiobolus graminis* | Varied from 1.6 to 18.3% in individual fields |
| Gordon (20) | 1929 | Man. | Foot-rot complex | Trace to 100% plants in certain fields.—25% of fields examined showed infection of 50% or more |
| Doughty *et al.* (13) | 1929 | England | Foot-rot complex | Loss amounting to 30% of plants |
| Sanford (12) | 1930 | Alta. | Foot-rot complex | Found in 271 fields out of 416— 2% damage |

attack wheat, rather than to a significant loss in fertility of the soil. Why certain micro-organisms should increase or decrease according to soil type, environment, crop or cultural practice, is at present imperfectly understood. However, the work of Sanford and Broadfoot (55), Broadfoot (7, 8), Porter (43), Henry (28) and others suggests that other soil-inhabiting micro-organisms may play an important role in this connection.

Investigations for practical means of combatting the losses from these foot rots have followed two main lines, namely, the securing of naturally resistant varieties, and the devising of crop rotations and cultural practices

suitable to western agriculture. Evidence is that the successful issue of the former method will require a long time, and there is the possibility that varieties may not be obtained which are wholly resistant under all environmental conditions. Hence, it may be necessary to depend more or less on crop rotation and cultural practices for satisfactory control of these diseases.

Although certain investigators in Australia, Europe, the United States of America, and Canada, have recommended various crop rotations and cultural practices to reduce some of the foot rots mentioned, it is felt that, as observations were made under local conditions, and as often only one disease was concerned, such recommendations may not be applicable to the situation in western Canada, or to the foot-rot complex as a whole as it develops naturally in a crop sequence during several years. Consequently, this laboratory initiated, with the co-operation of the Dominion Experimental Stations at Morden, Manitoba; Indian Head, Swift Current, and Scott in Saskatchewan; and at Lethbridge, Alberta, in 1927, and the Alberta Schools of Agriculture at Olds and Vermilion in 1929, an intensive and uniform crop rotation project, where the development of the foot-rot complex might be studied naturally under a wide range of soil and climatic conditions.

## Material and Methods

*Locations of Project and Soil Type*

The locations of the project, soil type, altitude, and approximate average annual precipitation were as follows.—Morden, in S.W. Manitoba; black soil belt, alt. 992 ft., precip. 19 in.: Indian Head in S. Saskatchewan; silty clay loam, alt. 1,927 ft., precip. 17 in.: Swift Current in S.W. Sask.; brown clay loam, alt. 2,432 ft., precip. 15 in.: Scott in W. Central Sask.; brown loam, alt. 2,164 ft., precip. 14 in.: Lethbridge in S. Alberta; light brown silty loam, alt. 2,938 ft., precip. 16 in.: Olds in Central Alta.; black loam, alt. 3,413 ft., precip. 17 in.: Vermilion in E. Central Alta., brown loam, alt. 2,029 ft., precip. 16 in. Precipitation from April to September, inclusive, for the four years, 1928 to 1931, for these seven stations, is shown in Fig. 1.

*Outline of Project*

The various crop sequences and cultural practices used, each with its reference number, are listed as follows:—

*Two-year rotations.* 1, Summerfallow, wheat; 2, oats, wheat; 3, barley, wheat; 4, wheat, barley; 5, wheat, wheat; 6, wheat, wheat.

*Six-year rotations.* 7, Western rye, w. rye, wheat, oats, summerfallow, wheat seeded with w. rye; 8, oats, summerfallow, wheat seeded with w. rye, w. rye, w. rye, wheat; 9, continuous wheat.

*Three-year rotations.* 10, Wheat, summerfallow, wheat; 11, wheat, summerfallow manured, wheat; 12, summerfallow, summerfallow, wheat; 13, summerfallow, wheat, wheat; 14, summerfallow manured, wheat, wheat; 15, oats, oats, wheat; 16, sweet clover, s. clover, wheat; 17, w. rye, w. rye, wheat; 18, 19 and 20, continuous wheat.

*Cultural practices (second wheat crop after summerfallow).* 21, Average rate, date and depth of seeding; 22, light rate, average date and depth of seeding; 23, heavy rate, average date and depth of seeding; 24, average rate and date of seeding, but sown deep; 25, average rate and date of seeding, but sown shallow; 26, average rate, date and depth of seeding; 27, average rate, and depth of seeding, but sown late; 28, average rate, and depth of seeding, but sown early; 29, average rate, date, and depth of seeding but

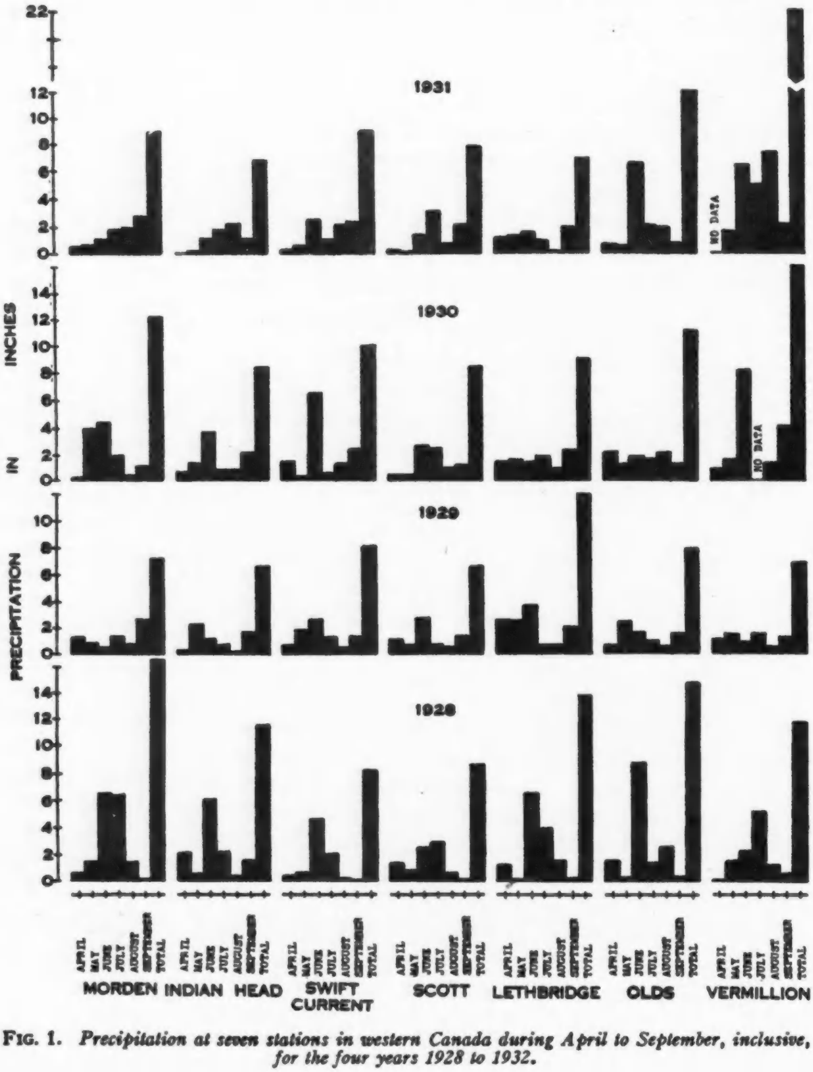



FIG. 1. *Precipitation at seven stations in western Canada during April to September, inclusive, for the four years 1928 to 1932.*

packed "heavy"; 30, average rate, date, and depth of seeding but packed "light"; 31, average rate, date, and depth of seeding not packed.

*Cultural practices (first wheat crop after summerfallow).* 32, Average rate, date and depth of seeding; 33, light rate, average date and depth of seeding; 34, heavy rate, average date and depth of seeding; 35, average rate, and date of seeding, but sown deep; 36, average rate, and date of seeding, but sown shallow; 37, average rate, date, and depth of seeding; 38, average rate and depth of seeding, but sown late; 39, average rate and depth of seeding, but sown early; 40, average rate, date and depth of seeding, but packed "heavy"; 41, average rate, date and depth of seeding, but packed "light"; 42, average rate, date and depth of seeding, not packed.

The average "rate", "date" and "depth" of seeding means that normally used at a station. "Heavy packing" was twice the weight of the "light packing", where known weights were added to the packer. The manure, where applied, was broadcast at the rate of 12 tons per acre, before the land was plowed for summerfallow. "Early" and "late" seeding means seeding 10 days earlier, and 10 days later, respectively, than the average time for the station. "Heavy" and "light" seeding means one-quarter bushel per acre more or less seed, respectively, than normally used at the station. "Shallow" and "deep" seeding means $\frac{3}{4}$–1 in. below, or above, the average depth for the station.

The results were obtained from four systematically distributed plots, each $\frac{1}{100}$ acre for each unit of the entire experiment. That part of the project dealing with cultural practices, *viz.*, 21–42, was, of necessity, omitted from Morden, Lethbridge, Vermilion and Olds. The plot at Swift Current was appropriated after the third year for an aviation field. Owing to economy measures at Indian Head the project there was discontinued after 1931.

A variety of spring wheat commonly grown in the district represented by the station was used, *viz.* Mindum, a durum wheat, at Morden; Marquis, at Indian Head, Swift Current, Lethbridge and Olds; Ruby, at Scott; and Renfrew, at Vermilion.

Field notes were taken just before the plants were wholly mature. Twenty plants were chosen at random from each of the four replicate plots of a unit, making a total of 80 plants from each unit of the experiment. The crowns and subcrowns were cut longitudinally, and the secondary roots examined and all rated numerically for degree of infection. An adequate representative sample of the basal portion of the plants from each plot was brought to the laboratory and isolations made from them. The results from these isolations are reported in Part IV of this series. The yield was taken at most of the stations.

### *Methods of Estimating Foot-rot Damage*

In America and Europe a uniform method of recording the severity of cereal rusts is in general use, but in the case of foot rots it is sometimes described by the terms "trace", "medium" or "severe". Others indicate it in per-

centage derived from estimated numerical values of arbitrary classes of severity and surviving plants. Any numerical system lends itself well to statistical treatment. McKinney (33) and Christensen (10) have adopted the latter method, each with certain marked modifications, the chief difference being that Christensen uses more classes than McKinney, which would seem one way of reducing the error of personal judgment. Then, too, the method of McKinney would seem better adapted to estimating damage in the seedling stage. With any system, important difficulties arise in determining the actual severity of disease on mature plants grown in the field. For example, the relation between the actual degree of injury to the crown tissue, and the color of this tissue, or its relation to the degree of shrivelling of the grains, is extremely difficult to estimate with any degree of certainty. That is to say, the relation may or may not be sufficiently close. Therefore, it is a question whether the rating should not be entirely based on the condition of the crown and secondary roots. In any case, it would seem highly desirable that a uniform system of recording numerically, in the seedling stage, and also in the mature stage, the severity of the foot rot be officially sanctioned for general use by a recognized body.

*Importance of Color*

A preliminary examination was made of the relation of the infection rating to discoloration of basal tissue, and also its relation to the general condition of the spike and grains. Material used for the purpose consisted of 200

TABLE II

DEGREE OF INFECTION AND COLOR OF CERTAIN PLANT PARTS, AND SOUNDNESS OF SPIKES OF PLANTS FROM WHEAT AFTER SUMMERFALLOW AND CONTINUOUS WHEAT SEQUENCES

| Plant parts | Degree of infection[1] | | Degree of color[2] | |
|---|---|---|---|---|
| | Wheat after summerfallow | Continuous wheat | Wheat after summerfallow | Continuous wheat |
| A. Primary roots | 3.72 light to medium | 6.88 heavy to dead | 1.50 brown | 2.77 light black |
| B. Subcrown internode | 3.00 light to medium | 4.72 medium to heavy | 1.23 light brown | 2.45 light black |
| C. Lower half of crown | 5.42 medium to heavy | 7.04 heavy to dead | 1.30 light brown | 2.09 brown |
| D. Upper half of crown | 4.88 medium | 5.76 heavy | 1.27 light brown | 2.08 brown |
| E. 1st set of secondary roots | 5.61 medium to heavy | 6.99 heavy to dead | 1.53 light brown | 2.29 brown |
| F. 1st internode above crown | 1.15 trace to light | 2.74 light to medium | 0.59 very light brown | 1.53 brown |
| G. 2nd set of secondary roots | 4.40 medium | 5.19 medium to heavy | 1.08 light brown | 1.59 brown |
| H. 3rd set of secondary roots (if present) | 4.28 medium to heavy | 4.79 medium to heavy | 0.83 very light brown | 1.56 brown |
| Average[3] | 4.05 medium | 5.51 medium to heavy | 1.16 light brown | 2.05 brown |

[1] *$Z = 1.88$; $P = 1193$.* [2] *$Z = 3.67$; $P$ = very great.*

[3] *Soundness of spike:—wheat after summerfallow, 89.8% healthy; continuous wheat, 75.5% healthy.*

plants grown in 1928 from each of two long-time rotations at the Dominion Experimental Station, Lacombe. The first sample was from a rotation in which summerfallow alternated with wheat, and the other sample from continuous wheat. Certain parts of the general foot and root area of these plants (indicated in Table II), were rated separately for color and also for severity of infection. The color was numerically rated as follows: normal 0, light brown 1, brown 2, dark brown 3, light black or dark gray 4, and black 5.

As indicated in Table II, the average color rating of the tissue parts was nearly twice as great on the 200 plants from the sequence wheat after wheat as it was on those from the sequence wheat after summerfallow. When compared on the basis of probable error according to "Student's" method (61), $Z$ had a value of 3.67, and the odds were very great that the difference was significant. In the continuous wheat sequence the color of the basal parts ranged from brown to light black, while in the sequence where wheat alternated with summerfallow, it was brown in only one instance, namely, the primary roots, while the other parts were either very light brown or light brown.

The infection rating given the corresponding parts from each of the series mentioned was, as in the case of color, more pronounced for wheat after wheat than for wheat after summerfallow. Based on an average for all parts used, the ratio was approximately 1.3:1, where the $Z$ value was 1.88, and the odds 1193:1. The average for color, on a similar basis for the two sequences, was in the ratio of 1.8:1, and with a $Z$ value of 367, the odds were very great that the difference was significant.

However, even though there be general agreement in color and infection rating, there are many instances where the degree of color may not correctly indicate the severity of infection. A good example of this is supplied by plant part $D$, upper half of crown, where the color rating for brown was 2.08 in the one case, and 1.27 for light brown in the other, while the infection ratings were 5.76 and 4.88, respectively.

*Soundness of Spikes*

The general soundness of spikes, including color and condition of kernels, appeared to be even less closely related than the color of the basal part to the infection rating, based on the condition of the crown and root tissue. The ratio of healthy spikes from wheat after summerfallow and from continuous wheat was 1:1.2, while for unhealthy spikes it was 1:2.4. However, the infection rating of the two lots, based wholly on the crown and root tissue, was approximately 1:1.3. Thus, in spite of the fact that certain cases arise where the relation might be fairly close, the actual condition of the crown and root tissue is not always reflected by the condition of the spike. The same may be said regarding yield.

Consequently, in this experiment the infection rating was based wholly on the condition of the crown and secondary roots. The primary roots were ignored, since on mature plants in the field these may be an uncertain quantity. The various degrees of infection were rated as follows:—clean 0, trace 1,

EFFECT OF CROP ROTATION AND CULTURAL PRACTICE ON THE DEVELOPMENT OF FOOT ROT OF WHEAT AT SEVEN STATIONS IN WESTERN CANADA DURING 1928 TO 1932, INCLUSIVE. AVERAGE YEARLY RESULTS ARE GIVEN

| | Infection rating | | | | | | | Number of fertile culms | | | | | Number of total culms | | | | | | | Yield | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A* | 1928 | 1929 | 1930 | 1931 | 1932 | Av. | B† | 1930 | 1931 | 1932 | Av. | B | 1928 | 1929 | 1930 | 1931 | 1932 | Av. | B | 1928 | 1929 | 1930 | 1931 | 1932 | Av. | B |
| 2-year rotations | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 1.0 | 2.8 | 2.5 | 1.3 | 1.9 | 1.9 | 28 | 1.6 | 1.6 | 1.8 | 1.7 | 18 | 2.0 | 1.5 | 2.0 | 2.8 | 2.8 | 2.2 | 28 | 24.8 | 16.5 | 32.2 | 35.4 | 37.0 | 29.2 | 21 |
| 2 | 0.5 | 2.1 | 2.7 | 2.1 | 2.4 | 2.0 | 27 | 1.7 | 1.3 | 1.4 | 1.5 | 17 | 1.9 | 1.3 | 1.9 | 2.0 | 2.3 | 1.9 | 27 | 24.5 | 9.4 | 26.2 | 24.6 | 33.5 | 23.6 | 21 |
| 3 | 0.6 | 2.4 | 4.7 | 4.5 | 5.5 | 3.5 | 27 | 1.4 | 1.3 | 1.3 | 1.3 | 17 | 1.7 | 1.2 | 1.8 | 2.1 | 2.2 | 1.8 | 27 | 22.4 | 10.5 | 25.3 | 24.6 | 33.1 | 23.2 | 21 |
| 4 | 0.6 | 2.3 | 6.1 | 5.7 | 6.6 | 4.3 | 25 | 1.5 | 1.3 | 1.3 | 1.4 | 17 | 1.6 | 1.3 | 1.9 | 2.1 | 2.3 | 1.8 | 25 | 25.8 | 12.6 | 28.0 | 41.5 | 47.7 | 31.1 | 20 |
| 5 | 0.6 | 2.5 | 5.1 | 4.7 | 5.1 | 3.6 | 27 | 1.4 | 1.4 | 1.3 | 1.4 | 17 | 1.8 | 1.3 | 1.7 | 2.2 | 2.2 | 1.8 | 27 | 24.2 | 9.4 | 23.9 | 23.4 | 32.1 | 22.6 | 21 |
| 6 | 0.8 | 2.4 | 5.2 | 4.9 | 5.3 | 3.7 | 27 | 1.4 | 1.3 | 1.3 | 1.3 | 17 | 2.0 | 1.3 | 1.8 | 2.1 | 2.3 | 1.9 | 27 | 23.3 | 8.8 | 25.7 | 25.9 | 28.2 | 22.4 | 21 |
| 6-year rotations | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | 1.8 | 4.4 | 3.7 | 2.0 | 2.2 | 2.8 | 25 | 1.7 | 1.7 | 1.6 | 1.7 | 17 | 2.1 | 1.5 | 2.2 | 2.6 | 2.6 | 2.2 | 25 | 34.6 | 15.7 | 39.3 | 31.0 | 34.6 | 31.0 | 18 |
| 8 | 1.5 | 3.1 | 5.2 | 4.8 | 5.3 | 4.0 | 24 | 1.5 | 1.4 | 1.4 | 1.4 | 16 | 1.7 | 1.4 | 1.9 | 2.2 | 2.3 | 1.9 | 24 | 33.1 | 12.9 | 25.3 | 27.6 | 24.4 | 24.7 | 18 |
| 9 | 0.1 | 5.0 | 5.3 | 4.6 | 5.4 | 4.1 | 11 | 1.4 | 1.6 | 1.3 | 1.4 | 9 | 2.7 | 2.2 | 1.7 | 2.3 | 2.2 | 2.2 | 11 | | 8.5 | 41.1 | 56.9 | 37.8 | 36.1 | 6 |
| 3-year rotations | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | 1.1 | 2.6 | 2.3 | 1.4 | 2.1 | 1.9 | 28 | 1.7 | 1.9 | 1.7 | 1.8 | 18 | 2.4 | 1.4 | 2.2 | 2.8 | 2.6 | 2.3 | 28 | 25.4 | 15.2 | 36.0 | 35.2 | 31.6 | 28.7 | 21 |
| 11 | 1.4 | 3.3 | 2.6 | 1.6 | 2.3 | 2.2 | 25 | 1.7 | 2.0 | 1.9 | 1.9 | 17 | 2.0 | 1.5 | 2.2 | 3.1 | 2.8 | 2.3 | 25 | 29.1 | 20.2 | 42.3 | 36.2 | 34.3 | 32.4 | 18 |
| 12 | 1.5 | 2.4 | 2.0 | 1.4 | 2.0 | 1.9 | 27 | 1.6 | 1.9 | 1.8 | 1.8 | 18 | 2.0 | 1.6 | 2.2 | 2.8 | 2.7 | 2.3 | 27 | 26.0 | 17.4 | 46.5 | 38.2 | 35.6 | 32.7 | 20 |
| 13 | 1.0 | 2.4 | 4.8 | 4.2 | 5.0 | 3.5 | 26 | 1.4 | 1.5 | 1.3 | 1.4 | 17 | 1.9 | 1.5 | 1.9 | 2.4 | 2.3 | 2.0 | 26 | 20.5 | 9.8 | 31.2 | 27.2 | 27.6 | 23.3 | 20 |
| 14 | 0.7 | 3.1 | 4.6 | 4.3 | 4.5 | 3.4 | 23 | 1.5 | 1.5 | 1.4 | 1.5 | 16 | 1.7 | 1.3 | 2.0 | 2.4 | 2.4 | 2.0 | 23 | 23.7 | 11.4 | 35.8 | 27.0 | 30.7 | 25.7 | 17 |
| 15 | 1.0 | 2.3 | 2.3 | 2.2 | 2.3 | 2.0 | 26 | 1.5 | 1.5 | 1.4 | 1.5 | 17 | 2.2 | 1.4 | 1.8 | 2.3 | 2.3 | 2.0 | 26 | 24.3 | 9.8 | 29.6 | 26.5 | 28.0 | 23.6 | 20 |
| 16 | 0.9 | 2.8 | 2.3 | 2.2 | 2.6 | 2.2 | 27 | 1.5 | 1.7 | 1.7 | 1.6 | 18 | 2.0 | 1.5 | 2.0 | 2.7 | 2.7 | 2.2 | 27 | 24.8 | 10.7 | 35.3 | 32.5 | 33.0 | 27.3 | 20 |
| 17 | 0.8 | 2.4 | 4.6 | 4.4 | 5.3 | 3.5 | 27 | 1.4 | 1.5 | 1.3 | 1.4 | 18 | 2.1 | 1.6 | 1.9 | 2.5 | 2.3 | 2.1 | 27 | 19.8 | 12.3 | 26.7 | 28.7 | 28.4 | 23.2 | 20 |
| 18 | 0.0 | 3.4 | 5.3 | 5.1 | 5.2 | 3.8 | 11 | 1.5 | 1.5 | 1.3 | 1.4 | 9 | 2.1 | 2.4 | 1.9 | 2.5 | 2.3 | 2.2 | 11 | | 15.3 | 42.9 | 57.7 | 31.8 | 36.9 | 6 |
| 19 | 0.0 | 4.0 | 5.6 | 5.1 | 5.0 | 3.9 | 11 | 1.5 | 1.5 | 1.4 | 1.5 | 9 | 2.7 | 1.9 | 1.8 | 2.6 | 2.3 | 2.3 | 11 | | 14.2 | 47.9 | 55.2 | 29.8 | 36.8 | 6 |
| 20 | 0.0 | 3.8 | 5.4 | 4.5 | 5.2 | 3.8 | 11 | 1.3 | 1.4 | 1.2 | 1.3 | 9 | 2.8 | 2.3 | 1.8 | 2.4 | 2.1 | 2.3 | 11 | | 18.7 | 38.4 | 49.0 | 33.1 | 34.8 | 6 |
| Cultural practices (Summerfallow, wheat, wheat) | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 21 | 0.9 | 1.2 | 4.5 | 2.9 | 5.2 | 2.9 | 11 | 1.3 | 1.1 | 2.0 | 1.5 | 5 | 1.6 | 1.1 | 1.9 | 2.0 | 3.0 | 1.9 | 11 | 20.2 | 4.2 | 16.2 | 13.8 | 19.0 | 14.7 | 11 |
| 22 | 0.8 | 1.0 | 4.4 | 3.0 | 5.2 | 2.9 | 11 | 1.4 | 1.5 | 1.8 | 1.6 | 5 | 1.7 | 1.2 | 1.9 | 2.4 | 2.8 | 2.0 | 11 | 18.9 | 4.9 | 16.0 | 15.9 | 19.2 | 15.0 | 11 |
| 23 | 0.7 | 1.4 | 4.2 | 3.2 | 5.2 | 2.9 | 11 | 1.1 | 1.2 | 1.7 | 1.3 | 5 | 1.5 | 1.1 | 1.4 | 1.9 | 2.7 | 1.7 | 11 | 21.3 | 4.0 | 16.9 | 14.7 | 17.8 | 14.9 | 11 |
| 24 | 1.0 | 1.9 | 4.1 | 3.2 | 5.7 | 3.2 | 11 | 1.4 | 1.3 | 1.5 | 1.4 | 5 | 1.9 | 1.1 | 1.9 | 2.2 | 2.5 | 1.9 | 11 | 19.6 | 4.3 | 18.4 | 13.1 | 18.3 | 14.7 | 11 |
| 25 | 0.9 | 1.4 | 4.2 | 3.1 | 5.7 | 3.1 | 11 | 1.4 | 1.2 | 1.8 | 1.5 | 5 | 1.8 | 1.1 | 1.8 | 2.1 | 2.8 | 1.9 | 11 | 17.8 | 4.8 | 18.7 | 12.4 | 17.7 | 14.3 | 11 |
| 26 | 0.8 | 1.0 | 4.3 | 3.1 | 5.6 | 3.0 | 11 | 1.3 | 1.3 | 1.6 | 1.4 | 5 | 1.9 | 1.1 | 1.8 | 2.2 | 2.6 | 1.9 | 11 | 19.6 | 4.1 | 18.6 | 14.2 | 19.1 | 15.1 | 11 |
| 27 | 0.7 | 2.2 | 2.4 | 2.1 | 2.5 | 2.0 | 20 | 1.7 | 1.7 | 1.9 | 1.8 | 13 | 1.3 | 1.1 | 2.1 | 2.4 | 2.9 | 2.0 | 20 | 16.9 | 4.9 | 19.3 | 16.8 | 19.2 | 15.4 | 11 |
| 28 | 1.2 | 2.1 | 4.8 | 4.7 | 5.3 | 3.6 | 20 | 1.5 | 1.6 | 1.5 | 1.5 | 13 | 2.1 | 1.2 | 1.9 | 2.4 | 2.5 | 2.0 | 20 | 17.0 | 3.4 | 16.5 | 11.5 | 18.8 | 13.4 | 11 |
| 29 | 1.5 | 1.9 | 5.0 | 4.1 | 5.4 | 3.6 | 20 | 1.3 | 1.6 | 1.4 | 1.4 | 13 | 1.8 | 1.4 | 1.7 | 2.5 | 2.4 | 2.0 | 20 | 21.5 | 3.8 | 19.0 | 15.4 | 16.3 | 15.2 | 11 |
| 30 | 1.2 | 1.7 | 5.1 | 4.3 | 5.1 | 3.5 | 20 | 1.3 | 1.5 | 1.6 | 1.5 | 13 | 1.8 | 1.4 | 1.7 | 2.3 | 2.5 | 1.9 | 20 | 21.4 | 4.5 | 18.9 | 14.8 | 16.0 | 15.1 | 11 |
| 31 | 1.1 | 1.8 | 4.6 | 2.8 | 5.6 | 3.2 | 11 | 1.4 | 1.4 | 1.7 | 1.5 | 5 | 1.7 | 1.1 | 1.8 | 2.3 | 2.8 | 1.9 | 11 | 19.3 | 4.8 | 17.7 | 13.0 | 18.6 | 14.7 | 11 |

A = *Treatments. These are given under "Outline of project" in context.* B = *Number of station-years.*

light− 2, light 3, light+ 4, medium− 5, medium 6, medium+ 7, heavy− 8, heavy 9, heavy+ 10. These data were further supplemented by the total number of culms, number of fertile culms, and yield.

## Experimental Results

For convenience, the summarized results of each crop sequence or cultural practice, for all the stations (totalling 28 station-years) will be discussed separately. The data taken at every station from 1928 to 1932, inclusive, on infection rating, total number of culms, number of fertile culms, and yield of wheat, are compiled in various tables*, and, as it is impossible to present these in detail here, only average results will be used in this report. However, it is deemed advisable to present in Table III the average results for each year.

The agreement in results among replicates of a given treatment at the various stations during one year was reasonably satisfactory, under the conditions of the experiment. An example of the variation among the four replicates of each of the two continuous wheat series at the various stations, in 1930, with $Z$ and $P$ values calculated as before by Student's method, is supplied in Table IV. Satisfactory explanation for the large variation at Vermilion is not available. However, in no other year did such an unusual variation occur, either in the replicates of these, or other sequences at any station. It may also be mentioned that the variation probably would be less in the continuous wheat sequence than it would be where wheat followed different crops. Naturally the wide range of soil and climatic conditions

TABLE IV

INFECTION INDEX FOR THE REPLICATES, MEANS, AND $Z$ AND $P$ VALUES CALCULATED BY "STUDENT'S" METHOD FOR TWO CONTINUOUS WHEAT SEQUENCES AT SEVEN STATIONS

| Station | Plot no. | Infection index | | | | | Values for | |
|---|---|---|---|---|---|---|---|---|
| | | Replicate | | | | | | |
| | | A | B | C | D | Av. | $Z$ | $P$ |
| Morden | 5 | 4.7 | 3.4 | 3.7 | 4.5 | 4.1 | .02 | 1.02 |
| | 6 | 3.7 | 2.8 | 4.2 | 5.1 | 4.0 | | |
| Indian Head | 5 | 5.4 | 5.5 | 6.1 | 6.9 | 6.0 | .69 | 5.29 |
| | 6 | 5.7 | 5.4 | 5.4 | 5.9 | 5.6 | | |
| Swift Current | 5 | 6.5 | 6.0 | 5.9 | 7.3 | 6.7 | .05 | 1.12 |
| | 6 | 6.7 | 6.0 | 6.8 | 6.0 | 6.4 | | |
| Scott | 5 | 4.2 | 4.3 | 3.2 | 4.9 | 4.2 | .32 | 2.24 |
| | 6 | 4.3 | 4.9 | 3.7 | 4.3 | 4.3 | | |
| Lethbridge | 5 | 5.3 | 5.5 | 5.9 | 5.3 | 5.5 | .10 | 1.29 |
| | 6 | 5.9 | 5.9 | 5.8 | 4.6 | 5.6 | | |
| Olds | 5 | 4.4 | 4.9 | 4.1 | 4.2 | 4.4 | .10 | 1.29 |
| | 6 | 4.8 | 4.0 | 5.2 | 4.4 | 4.6 | | |
| Vermilion | 5 | 4.7 | 4.6 | 4.6 | 3.9 | 4.5 | 2.62 | 102.0 |
| | 6 | 6.0 | 6.5 | 4.7 | 5.1 | 5.0 | | |

**The results for each crop sequence and station for the years 1928 to 1932, inclusive, are on file and are available at the Dominion Laboratory of Plant Pathology, Edmonton, Alberta.*

which existed between one station and another in a given year, tended to affect the infection rating, yield and other data from all treatments. But the significance of these climatic and soil factors cannot be discussed fully at this time. Suffice it to say, such variations would not seem to affect the conclusions in this paper.

### *Crop Sequence*

*Continuous wheat.* Guyot (25), Gram (21), Gram, Jørgensen and Rostrup (23), and Tedin (62) in Europe, and Russell (48), and Sanford (52) in Canada, have pointed out that wheat suffers most from foot rot where this crop is grown continuously on the same soil. The average results for the continuous wheat sequence, treatments Nos. 5 and 6 (Table V), for the years 1928 to 1932 inclusive, indicate that this sequence gave the highest infection rating and the lowest yield and number of fertile culms of any in the entire experiment.

TABLE V.

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 5 | Continuous wheat | 3.7 | 1.4 | 1.9 | 20.4 |
| 6 | Continuous wheat | 3:9 | 1.4 | 1.9 | 20.7 |

NOTE:—*I.R., F.C., T.C., and Y.B., indicate infection rating, fertile culms, total culms, and yield in bushels per acre, respectively. These abbreviations will be used subsequently in tabular listings.*

*Summerfallow alternating with wheat.* Gram and Rostrup (22), and Petersen (41) in Europe, and Fraser, Simmonds and Russell (18), and Sanford (52) in Canada state that take-all is less severe where wheat follows summerfallow than where it follows wheat. This is amply verified throughout this experiment. In fact, wheat grown after summerfallow was much less severely attacked than it was after any other crop or practice, the infection rating being 1.9 for the former, and 3.7 for continuous wheat sequence (treatments Nos. 1 and 5). Also, the average total number of culms, average number of fertile culms, and yield were uniformly greater where wheat followed summerfallow than where it followed wheat. This is indicated in Table VI.

TABLE VI

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 1 | Summerfallow alternating with wheat | 1.9 | 1.7 | 2.2 | 27.1 |
| 5 | Continuous wheat | 3.7 | 1.4 | 1.9 | 20.4 |

*Barley alternating with wheat*. Gram, Jørgensen and Rostrup (23), Moritz (36), and Heitz (27) in Europe, and Russell (48) in Canada, state that where wheat followed barley, the development of take-all was favored, although Petersen (41) in Sweden suggests that this disease can be practically eliminated by a crop of summer barley. Also, it is maintained that injury from *H. sativum* is frequently increased when wheat is grown after barley.

In the rotations described here the average infection rating on wheat grown after barley was 3.5, which is almost as great as it was on wheat grown after wheat, *viz*. 3.7 (treatments Nos. 3 and 5). The difference in average total number of culms, average number of fertile culms, and yield was very slight for the two sequences, being indicated by the results in Table VII.

TABLE VII

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 3 | Barley alternating with wheat | 3.6 | 1.4 | 1.8 | 21.1 |
| 5 | Continuous wheat | 3.7 | 1.4 | 1.9 | 20.4 |

*Oats alternating with wheat*. Heitz (27), Petersen (41), Sanford (52), Russell (48), and Simmonds (58) state that foot rot is greatly reduced where wheat follows oats. Richardson (44), Schaffnit (56), Kirby (32), Fraser, Simmonds and Russell (18), Wolf and Lehman (64), and Russell (47), state that in general oats are highly resistant or immune to *O. graminis*. However, Jones (31), in Wales, described the formation of perithecia of this parasite on oats, and, in Germany (36), Australia (1), and Denmark (3) certain varieties were found susceptible.

The infection rating on wheat after oats shows quite conclusively that this crop greatly reduces foot-rot injury, and in this respect is fairly comparable to the effect of summerfallow. For example, the infection rating was 2.0, while for continuous wheat it was 3.7. In Table VIII is a comparison of averages of infection rating, number of fertile culms, number of total culms, and the yield, from this sequence, with the continuous wheat sequence (treatments Nos. 2 and 5).

TABLE VIII

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 2 | Oats alternating with wheat | 2.0 | 1.5 | 1.9 | 21.5 |
| 5 | Continuous wheat | 3.7 | 1.4 | 1.9 | 20.4 |

*Two crops of oats followed by wheat.* The effect of two crops of oats on the infection rating was apparently identical with that of one crop of oats. The results from this sequence are compared in Table IX with those from the continuous wheat sequence, and also with those from one crop of oats (treatments Nos. 15, 2 and 5).

TABLE IX

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 15 | Wheat after two crops of oats | 2.1 | 1.4 | 2.0 | 21.8 |
| 2 | Oats alternating with wheat | 2.0 | 1.5 | 1.9 | 21.5 |
| 5 | Continuous wheat | 3.7 | 1.4 | 1.9 | 20.4 |

*Two crops of sweet clover followed by wheat.* The average infection rating in this sequence was very similar to that in the sequence in which summerfallow alternated with wheat (treatments Nos. 16 and 1). The averages of the total number of culms and number of fertile culms were increased slightly, and the yield, which depends upon the catch of sweet clover secured, was on the whole improved (Table X).

TABLE X

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 16 | Wheat after two years of sweet clover | 2.1 | 1.7 | 2.3 | 25.4 |
| 1 | Wheat after summerfallow | 1.9 | 1.7 | 2.2 | 27.1 |
| 5 | Continuous wheat | 3.7 | 1.4 | 1.9 | 20.4 |

*Two crops of western rye followed by wheat.* Samuel (50), Russell (48), Padwick and Henry (38), and others have reported that take-all is favored when wheat follows western rye. Also, some observers contend that damage from either *H. sativum* or *Fusarium* spp. is increased by this crop. The infection rating from this sequence was about as high as it was from the continuous wheat sequence or from the sequence wheat after barley (treatments Nos. 17, 3 and 5). The comparison is shown in Table XI.

TABLE XI

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 17 | Wheat after two crops of western rye | 3.9 | 1.4 | 2.1 | 22.2 |
| 3 | Wheat after barley | 3.5 | 1.4 | 1.8 | 21.1 |
| 5 | Continuous wheat | 3.7 | 1.4 | 1.9 | 20.4 |

*Wheat after two years of summerfallow.* This sequence was included to determine whether two years of summerfallow would reduce the infection rating even more than one year of summerfallow. The results, which are given in Table XII, indicate that, under average conditions of this experiment, one year of summerfallow is as effective as two for the purpose indicated (treatments Nos. 12 and 1).

TABLE XII

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 12 | Wheat after two years of summerfallow | 1.9 | 1.7 | 2.4 | 29.8 |
| 1 | Summerfallow alternating with wheat | 1.9 | 1.7 | 2.2 | 27.1 |
| 5 | Continuous wheat | 3.7 | 1.4 | 1.9 | 20.4 |

*One year of summerfallow followed by two crops of wheat.* Although the average infection rating on the first crop of wheat after summerfallow was low, *viz.* 1.9, that on the second crop of wheat in this sequence was increased to 3.7 (treatments Nos. 1 and 13). Also the averages of the total number of culms and number of fertile culms, and yield were reduced, as indicated in Table XIII.

TABLE XIII

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 13 | Second wheat crop after summerfallow | 3.7 | 1.4 | 2.0 | 22.0 |
| 1 | Summerfallow alternating with wheat | 1.9 | 1.7 | 2.2 | 27.1 |
| 5 | Continuous wheat | 3.7 | 1.4 | 1.9 | 20.4 |

The data given show how quickly foot rot increases normally. From the standpoint of foot rots and also economy, a crop of oats the second year after summerfallow, where practicable, would provide a better sequence.

*Summerfallow (manured) followed by two crops of wheat.* Rosen and Elliott (45), and Fellows (16) state that stable manure, applied to soil infested with *O. graminis*, greatly reduced the severity of take-all. Peyronel (42) recommends nitrogenous fertilizers for this purpose. Moritz (36) did not observe consistent effects of such application, while Benoist and Bailly (5), Erhard-Frederiksen (14), and Tedin (62) state that manure favors the development of take-all. Apparently there are no very definite observations respecting the effect of manure on the foot rots caused by *H. sativum* or *Fusarium* spp.

In these experiments, the rating was practically as low the first year on manured summerfallow, as it was on the summerfallow without manure (treatments Nos. 11 and 10). The rating on the second crop of wheat on manured summerfallow was practically the same as for a similar sequence where no manure was applied (treatments Nos. 14 and 13). Possibly a more effective test would be to apply manure to a continuous wheat sequence. The comparison is shown in Table XIV.

TABLE XIV

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 11 | First wheat crop after manured summerfallow | 2.1 | 1.9 | 2.5 | 32.2 |
| 10 | First wheat crop after summerfallow | 1.9 | 1.8 | 2.4 | 27.4 |
| 14 | Second wheat crop after manured summerfallow | 3.8 | 1.5 | 2.0 | 24.8 |
| 13 | Second wheat crop after summerfallow | 3.7 | 1.4 | 2.0 | 22.0 |

From these data is is evident that the yield was slightly greater for the sequences in which manure was used than for those in which it was not used.

*Summerfallow followed by wheat seeded down with western rye.* The infection rating for wheat in this sequence (treatment No. 7), cannot be compared fairly with other sequences in this project. However, where wheat was sown after two years of western rye in treatment No. 8, the rating was 4.3, while it was 2.4 in treatment No. 7. In the latter instance the limited available soil moisture after the second year of western rye probably would affect severely the wheat and favor foot-rot under average conditions in the prairie provinces. On this account, and because of less foot rot, and a greater yield, perhaps a more suitable procedure would be to use sweet clover instead of western rye (treatment No. 16). The averages of infection rating, total number of culms and number of fertile culms, and yield for the treatments mentioned are given in Table XV.

TABLE XV

| Treatment | Rotation | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 7 | Summerfallow followed by wheat with w. rye (six-year rotation) | 2.4 | 1.7 | 2.2 | 30.5 |
| 8 | Wheat after two years w. rye (six-year rotation) | 4.3 | 1.3 | 2.0 | 25.1 |
| 17 | Wheat after two years w. rye (three-year rotation) | 3.9 | 1.4 | 2.1 | 22.2 |
| 16 | Wheat after two years sweet clover (three-year rotation) | 2.1 | 1.7 | 2.3 | 25.4 |

*Cultural Practices*

Parisot (39), and Hulsenberg (29) in Europe, state that take-all is favored where cultural practices provide conditions above the optimum for growth, while Tepper (63), and Pearson (40) of Australia, and Rosen and Elliott (45) at Arkansas, state that undernourished plants are more susceptible. Certain cultural practices, such as rate, date, depth of seeding, and firmness of soil, which might affect the vigor of the plants, were studied under field conditions.

The observations were made, in one instance on the second wheat crop after summerfallow (treatments Nos. 21–31, inclusive), and in the other case from wheat seeded on summerfallow (treatments Nos. 32–42, inclusive). Since the infection rating was not significantly different for any of the sequences in which wheat followed summerfallow, except possibly for late seeding, discussion will be confined to the results at Indian Head, Swift Current and Scott (11 station-years) from seeding on spring-plowed wheat stubble. The check used for each cultural practice was the average for the station. There were 12 systematically distributed checks. The averages of infection rating, number of fertile culms and number of total culms, and yield were in each case very similar, as may be seen in the results from treatments Nos. 21, 26, and 31.

*Date of seeding.* Parisot (39), Brunchant (9), Gaudineau and Guyot (19), and Feistritzer (15), in Europe, and Kirby (32) in America, state that winter wheat, sown early, is more susceptible to take-all than if it is sown late. According to Russell (47, 48) this is also true of spring wheat. Apparently no very definite information regarding *H. sativum* and *Fusarium* spp. is available. The average results from three dates of planting (treatments Nos. 26, 27, and 28) are shown in Table XVI.

TABLE XVI

| Treatment | Cultural practice | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 26 | Average | 2.3 | 1.3 | 1.8 | 13.8 |
| 27 | Late | 1.7 | 1.7 | 1.7 | 13.9 |
| 28 | Early | 2.8 | 1.4 | 1.8 | 12.0 |

In spite of the reduced infection rating from planting late, this practice, on account of early frost hazard, would not be safe in western Canada, except possibly in southern districts.

*Rate of seeding.* Guerrapain and Demolon (24), Mangin (35), Foëx (17), Sévegrand (57), Parisot (39), Erhard-Frederiksen (14), and Peyronel (42) in Europe, and Kirby (32) in America, state that with winter wheat take-all is favored by dense sowing. Obviously, the effect of rate of seeding on

yield and vigor of the plants, may be modified greatly by available soil moisture and nutrients. The average results obtained from average, light, and heavy seedlings (treatments Nos. 21, 22 and 23) are compared in Table XVII.

TABLE XVII

| Treatment | Cultural practice | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 21 | Average | 2.4 | 1.3 | 1.7 | 13.5 |
| 22 | Light | 2.3 | 1.5 | 1.8 | 13.2 |
| 23 | Heavy | 2.4 | 1.2 | 1.5 | 13.8 |

*Depth of seeding*. Russell (47, 49) states that, in pot culture, plants from wheat grains planted 4 in. deep, suffered from take-all more than when they were planted 2 in. deep. With respect to foot rot caused by *H. sativum* or *Fusarium* spp., field observations frequently suggest that very deep seeding increases the disease. However, in these experiments no definite results were obtained, possibly because the differences between "shallow", "deep" and "average" were not sufficient for an adequate test. The average results (treatments Nos. 24, 25, and 26) are given in Table XVIII.

TABLE XVIII

| Treatment | Cultural practice | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 24 | Deep | 2.6 | 1.4 | 1.7 | 15.8 |
| 25 | Shallow | 2.4 | 1.4 | 1.7 | 13.4 |
| 26 | Average | 2.3 | 1.3 | 1.8 | 13.8 |

*Packing*. Sometimes farmers maintain that foot rot is reduced when a loose soil is packed. Russell (47), by controlling the soil moisture, found little effect on take-all from compacting the soil in pot culture, except that it retarded the emergence of the plants. The results in Table XIX obtained from heavy, light, and no packing of the soil, at the average rate, date, and depth of seeding (treatments Nos. 29, 30 and 31), were, under the conditions of the experiment, very similar.

TABLE XIX

| Treatment | Cultural practice | I.R. | F.C. | T.C. | Y.B. |
|---|---|---|---|---|---|
| 29 | Heavy | 2.8 | 1.4 | 1.8 | 14.4 |
| 30 | Light | 2.6 | 1.4 | 1.7 | 14.7 |
| 31 | None | 2.7 | 1.4 | 1.7 | 13.7 |

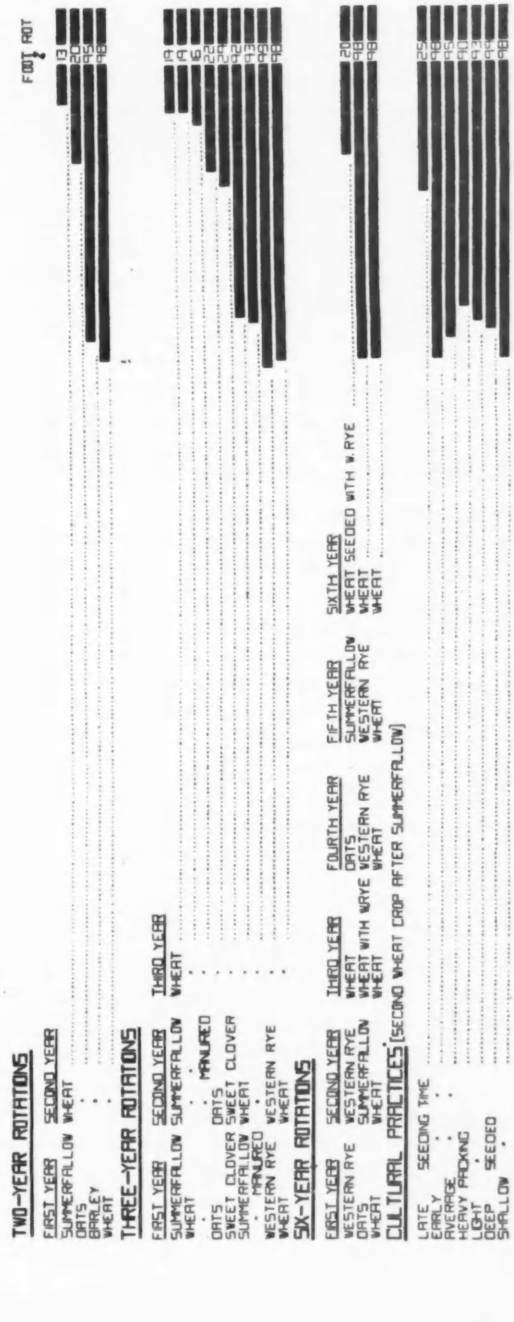



FIG. 2. *Effect of crop rotation and cultural practice on the development of foot rot of wheat at seven stations in western Canada for the years 1930 to 1932, inclusive.*

*Graphical Summary of Infection Rating for Project*

The summarized results, from the entire project for the years 1930 to 1932, inclusive, indicating the infection rating of wheat resulting from various crop sequences and cultural practices, are illustrated in Fig. 2. The percentages indicate the relative rating obtained and do not necessarily suggest the actual degree of loss.

## Discussion

It may be well to recall the wide range of soil and climatic conditions under which the foregoing results were obtained, and also the associated advantages and difficulties. Foot-rotting fungi were not added to the soil, or their development unnaturally stimulated. Also, the crop rotations and cultural practices were carried out in a way quite comparable to ordinary farming methods. In spite of natural difficulties in a field project of this kind, and the fact that some of the crop sequences are still too young to permit of final conclusions, the results given are reasonably well founded, and have a wide application in the prairie provinces of Canada.

Foot rot always developed most where wheat followed wheat, barley, or western rye grass, which in general verifies field observations. Also, the average number of fertile culms and total culms, and yield were uniformly lower in these sequences than in any others used. There was a marked decrease in foot rot and an increase in the number of fertile culms, total number of culms, and yield where wheat followed summerfallow. Under the conditions of the experiment, two years of summerfallow did not appear to be more effective in reducing foot rot than one year, and hence this procedure would seem both unnecessary and unsound, except possibly in more severe cases of foot rot than those studied in this investigation. However, the average number of fertile culms, total number of culms, and the yield were increased significantly in each instance. Where a crop of oats preceded wheat, foot rot was reduced practically as much as it was by summerfallow, and, as with summerfallow, two crops of oats did not appear to be more effective than one crop in reducing the infection rating. The number of fertile culms, total number of culms, and yield were very similar in both cases, and not significantly different for the continuous wheat sequence. Where wheat followed two crops of sweet clover the general effect on foot rot was the same as that obtained by summerfallow or oats. However, the yield, number of fertile culms, and total number of culms were increased over those observed where wheat followed oats.

The application of manure to summerfallow did not, in these studies, significantly modify the amount of foot rot on the two subsequent crops of wheat, beyond what occurred on similar sequences without manure. However, it is felt that these results should not be accepted as final for all conditions. The possibility that manure, applied to a continuous wheat sequence, would favor foot rot more than it does when applied to summerfallow, should not be overlooked.

Concerning the cultural practices available to the farmer, such as rate, date, and depth of seeding, and packing of the soil, the only evidence from these studies was that foot rot develops less on plants from late-sown wheat than on those from earlier seedings. However, this method cannot be safely used in western Canada because of frost hazard.

Finally, it should be mentioned that in these studies the progress of the foot rot was based wholly on the condition of the crown and secondary root tissue, and that the condition of the spike or the grains was not considered. The experimental evidence given earlier suggested this procedure as being the more reliable. Also, field observations of the foot rots, each year, indicate that frequently the progress of this disease in the crown may be marked, and yet the spike and grains may or may not reflect a corresponding effect.

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## References

1. Anonymous. South Australia Agr. Dept. J. 22 : 519. 1919.
2. Anonymous. Oregon Agr. Coll. Exptl. Sta. Director's Biennial Report, 1920-22 : 72-73. 1922.
3. Anonymous. Tidsskr. Planteavl, 36 : 506-554. 1930. (Rev. Applied Mycol. 9 : 701. 1930.)
4. Atanasoff, D. J. Agr. Research, 20 : 1-32. 1920.
5. Benoist, J. and Bailly, P. La Vie agricole, 11 : 266-268. 1922. (Rev. Applied Mycol. 2 : 11. 1923.)
6. Bolley, H. L. N. Dak. Agr. Exptl. Sta. Bull. 107 : 1-96. 1913.
7. Broadfoot, W. C. Can. J. Research, 8 : 483-491. 1933.
8. Broadfoot, W. C. Can. J. Research, 8 : 545-552. 1933.
9. Brunchant. Compt. rend. acad. agr. France, 12 : 812-822. 1926. (Rev. Applied Mycol. 6 : 83-84. 1927.)
10. Christensen, J. J. Minn. Agr. Exptl. Sta. Tech. Bull. 11 : 1-42. 1922.
11. Christensen, J. J. and Stakman, E. C. Phytopathology Abstr. 15 : 53. 1925.
12. Conners, I. L. and Eardley, E. A. 10th Ann. Rep. on the Prevalence of Plant Diseases in the Dominion of Canada, 1930. 10-11. 1931.
13. Doughty, L. R., Engledow, F. L. and Sansom, T. K. J. Agr. Sci. 19 : 472-490. 1929.
14. Erhard-Frederiksen, V. Ugeskr for Landmaend, 71 : 561-563. 1926. (Rev. Applied Mycol. 6 : 87. 1927.)
15. Feistritzer, W. Mitt. deut. Landw. ges. 47 : 791-793. 1932. (Rev. Applied Mycol. 12 : 157. 1933.)
16. Fellows, H. Phytopathology Abstr. 19 : 103. 1929.
17. Foëx, E. Soc. Path. Veg. France Bull. 6 : 52-56. 1919.

18. Fraser, W. P., Simmonds, P. M. and Russell, R. C. Phytopathology Abstr. 16 : 80-81. 1926.
19. Gaudineau, Mlle. and Guyot, L. Rev. Path. Vég. Ent. Agr. 12 : 317-342. 1925. (Rev. Applied Mycol. 5 : 415-416. 1926.)
20. Gordon, W. L. Rep. Dom. Botanist for 1929. Dept. Agr., Ottawa, 78-79. 1931.
21. Gram, E. Tidsskr. Planteavl, 35 : 141-268. 1929.
22. Gram, E. and Rostrup, Sofie. Tidsskr. Planteavl, 24 : 236-307. 1923. (Rev. Applied Mycol. 2 : 487-489. 1923.)
23. Gram, E., Jørgensen, C. A. and Rostrup, Sofie. Tidsskr. Planteavl, 33 : 781-841. 1927. (Rev. Applied Mycol. 7 : 222-223. 1928.)
24. Guerrapain, A. and Demolon, A. J. agr. prat. n.s. 26 : 566-567; 627-630. 1913.
25. Guyot, M. Rev. Path. Vég. Ent. Agr. 11 : 268-287. 1924. (Rev. Applied Mycol. 4 : 403-404. 1925.)
26. Heald, F. D. Wash. Agr. Exptl. Sta. 33rd. Ann. Report Bull. 180 : 42-44. 1923.
27. Heitz, K. Illus. Landw. Z. 47 : 488-489. 1927. (Rev. Applied Mycol. 7 : 87. 1928.)
28. Henry, A. W. Can. J. Research, 4 : 69-77. 1931.
29. Hulsenberg, H. Landw. Wothenschr. Sachsen. 88 : 607-609. 1930. (Rev. Applied Mycol. 10 : 651. 1931.)
30. Johnson, A. G. and Dickson, J. G. U.S. Dept. Agr. Farmers' Bull. 1224 : 1-16. 1921.
31. Jones, S. G. Ann. Botany, 40 : 607-629. 1926.
32. Kirby, R. S. Cornell Agr. Exptl. Sta. Mem. 88 : 1-45. 1925.
33. McKinney, H. H. J. Agr. Research, 26 : 195-217. 1923.
34. MacKinnon, E. Science Ind. Australia, 2 : 398-407. 1920.
35. Mangin, L. J. agr. prat. n.s. 27 : 236-239. 1914.
36. Moritz, O. Angew. Botany, 13 : 151-161. 1931. (Rev. Applied Mycol. 10 : 512-513. 1931.)
37. Moritz, O. Arb. Biol. Reichs. Land-Forstw. 20 : 27-48. 1932. (Rev. Applied Mycol. 12 : 19. 1933.)
38. Padwick, G. W. and Henry, A. W. Can. J. Research, 8 : 349-363. 1933.
39. Parisot. Compt. rend. acad. agr. France, 12 : 565-569. 1926. (Rev. Applied Mycol. 5 : 662. 1926.)
40. Pearson, A. N. Dept. Agr. Victoria Bull. 1 : 38-40. 1888.
41. Petersen, W. Nachr. über Schädlingsbekämpf, 5 : 33-34. 1930. (Rev. Applied Mycol. 9 : 516. 1930.)
42. Peyronel, B. Boll. staz. pat. veg. 6 : 285-336. 1926. (Rev. Applied Mycol. 6 : 342-343. 1927.)
43. Porter, C. L. Am. J. Botany, 11 : 168-188. 1924.
44. Richardson, A. E. V. South Australia Agr. Dept. J. 14 : 466-471. 1910.
45. Rosen, H. R. and Elliott, J. A. J. Agr. Research, 25 : 351-358. 1923.
46. Russell, R. C. Dept. Agr. Ottawa, Pamph. 85. 1927.
47. Russell, R. C. Rep. Dom. Botanist for 1928. Dept. Agr., Ottawa. 96-101. 1929.
48. Russell, R. C. Sci. Agr. 10 : 654-668. 1930.
49. Russell, R. C. Rep. Dom. Botanist for 1930. Dept. Agr., Ottawa. 78-81. 1931.
50. Samuel, G. J. Dept. Agr. South Australia, 27 : 1134-1147. 1924. (Rev. Applied Mycol. 4 : 88-89. 1925.)
51. Sanford, G. B. Rep. Dom. Botanist for 1925. Dept. Agr., Ottawa. 95-97. 1926.
52. Sanford, G. B. Rep. Dom. Botanist for 1926. Dept. Agr., Ottawa. 119-120. 1927.
53. Sanford, G. B. Rep. Dom. Botanist for 1927. Dept. Agr., Ottawa. 114. 1928.
54. Sanford, G. B. Rep. Dom. Botanist for 1928. Dept. Agr., Ottawa. 108-112. 1929.
55. Sanford, G. B. and Broadfoot, W. C. Sci. Agr. 11 : 512-528. 1931.
56. Schaffnit, E. Mitt. deut. Landw. ges. 45 : 1930. (Rev. Applied Mycol. 9 : 586. 1930.)
57. Sévegrand, P. La Vie agr. rurale, 24 : 341-342. 1920. (Rev. Applied Mycol. 3 : 579. 1924.)
58. Simmonds, P. M. Rep. Dom. Botanist for 1929. Dept. Agr., Ottawa. 107-108. 1931.
59. Stakman, E. C. U.S. Plant Disease Survey, Bull. Supplement, 21 : 139-254. 1922. (Mimeographed).
60. Stakman, Louise J. Minnesota Agr. Exptl. Sta. Bull. 191 : 1-18. 1920.
61. "Student". J. Am. Soc. Agron. 18 : 703-719. 1926.
62. Tedin, O. Landtmannen, 10 : 705-707. 1927. (Rev. Applied Mycol. 7 : 155-156. 1928.)
63. Tepper, J. G. O. Agr. Gaz. N. S. Wales, 3 : 69-72. 1892.
64. Wolf, F. A. and Lehman, S. G. 47th Ann. Rep. North Carolina Exptl. Sta. for the fiscal year ended June 30, 1924: 83-85. 1924. (Rev. Applied Mycol. 4 : 467-468. 1925.)

# STUDIES ON FOOT AND ROOT ROT OF WHEAT

## IV. EFFECT OF CROP ROTATION AND CULTURAL PRACTICE ON THE RELATIVE PREVALENCE OF *HELMINTHOSPORIUM SATIVUM* AND *FUSARIUM* SPP. AS INDICATED BY ISOLATIONS FROM WHEAT PLANTS[1]

By W. C. Broadfoot[2]


## Abstract

The crown and root tissue from 43,305 of 47,360 plants examined in this investigation yielded *Helminthosporium sativum*, *Fusarium culmorum* and other *Fusarium* spp., either alone or in combination with these or other fungi and bacteria. It was the exception for any mature plant, the surface tissue of which was disinfected, to be free from fungi or bacteria. None of the various crop sequences or cultural practices used in this study appeared to significantly affect more than another the relative prevalence of either *H. sativum* or *Fusarium* spp., as indicated by isolations from the crown tissue of wheat. However, as there was a marked tendency at certain stations each year for *H. sativum* or *Fusarium* spp. to predominate, it was concluded that certain factors of the environment were more effective than the crop sequence in modifying the relative prevalence of the two fungi mentioned in the crown and root tissue of wheat plants.


## Introduction

Commonly either *Helminthosporium sativum* P.K. and B. or *Fusarium* spp., or both, grow from the crowns and other basal parts of wheat plants suffering from foot rot, and yet they may or may not be parasitic. Ordinarily, these fungi, when the tissue is surface disinfected and incubated on solid media, grow to the exclusion of *Ophiobolus graminis* Sacc., even when the latter has caused most of the damage. On the other hand, *H. sativum* and *Fusarium* spp. are important foot-rotting pathogens, and they are extremely common in the soils of western Canada. However, there appear to be no very definite data in the literature as to whether the relative proportion of these are modified by certain crop rotations, cultural practices, regional location, climatic or other factors. Opportunity to obtain information on these interesting possibilities was afforded by the material available in the crop sequence and cultural studies which are described in Part III of this series (1).

## Material and Methods

A preliminary experiment was made to determine whether isolating from the crown tissue would indicate reasonably well the prevailing fungus in both crown and secondary roots. For this purpose an average of 46 plants was selected at random in 1928 on the long-time, continuous wheat plots at each of the following stations:—Brandon, Indian Head, Swift Current, Lethbridge,

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and Lacombe. Sections were cut from the roots more than 1 cm. from the crown, and from 1 cm. next to the crown. The crown was also cut longitudinally in halves. After disinfecting for two minutes in a 1 : 1000 mercuric chloride solution, these portions were placed on potato sucrose agar in separate plates. Half of each crown was placed cut side down, and the other half cut side up. After 10 days at room temperature, the colonies of *H. sativum*, *F. culmorum*, and other species of *Fusarium* growing from the sections were recorded for each plant part. In general, the identification of the fungi was based on macroscopic characters.

In 201 out of 280 cases, or 87.4%, apparently the same organism grew from both halves of the crown. In 186 out of 230 cases, or 80.9%, the same organism grew from the roots 1 cm. next to the crown as grew from the crown tissue. In 155 out of 230 cases, or 67.4%, apparently the same fungus inhabited the roots more than 1 cm. from the crown as was isolated from the crown. Of particular interest is the fairly close agreement in kind of organism in the two halves of the crown and in the roots 1 cm. long next to the crown. The correlation seemed to decrease in sections of the root more remote from the crown. Hence, in spite of certain variations it seemed best and reasonably safe, for the purposes of this study, to culture from the crown tissue only. The routine procedure consisted in taking the main tiller, removing the secondary roots close to the crown, the subcrown internode about 1 cm. below it, and also the culm about 1 cm. above the crown. During 1928 and 1929, determinations were made on only 10 random plants from each replicate of a sequence or practice, but from 20 plants in 1930, 1931 and 1932.

The crown parts were disinfected in mercuric chloride solution as before for two minutes, and incubated for 12 days in Petri plates on potato sucrose agar. The colonies of *H. sativum*, *F. culmorum* and other *Fusarium* spp. were recorded, and some other fungi were identified.

Owing to the practical impossibility of identifying with certainty all isolations of what apparently was *H. sativum* and *F. culmorum*, not to mention other *Fusarium* spp., in a study of this magnitude, the following comparisons will be based only on the isolations tentatively identified as *H. sativum* and *Fusarium* of the *culmorum* type and other *Fusarium* spp. While there may have been cases of mistaken identity of both fungi mentioned, the classification made of the two fungi, so different in color and general growth characteristics, will probably be sufficiently accurate for the purposes of this study.

Because of difficulties mentioned, there is doubt about the wisdom of attempting to classify even roughly the *culmorum* type of *Fusarium* from among the *Fusarium* species present. However, the results obtained indicate how common this type is in the crown tissue of wheat, while not obscuring the relative prevalence of *H. sativum*, or the *Fusarium* spp. as a group.

The results, based on the total colonies of both *H. sativum* and *Fusarium* spp. will be given to the nearest decimal in percentage for *H. sativum* and *F. culmorum*. The percentage of other or all *Fusarium* spp. can be estimated readily where not listed.

## Experimental Results

*Fungi Commonly Isolated*

The crown and root tissue from 43,305 of 47,360 plants examined in this study yielded *H. sativum*, *F. culmorum* and *Fusarium* spp., either alone or in combination with these and other identified and unidentified fungi and bacteria, so that it may be safely said that it was the exception for any mature plant, the surface tissue of which was treated, to be free from fungi or bacteria. *H. sativum* and *Fusarium* of the *culmorum* type, and also other *Fusarium* spp. were usually isolated from plants, the basal tissue of which bore signs of foot-rot infection. Sometimes one or more of the following grew from the tissue:—*H. sativum*, *Fusarium* spp., *Penicillia*, *Alternaria*, *Rhizoctonia* sp., *Macrosporium* sp., *Cladosporia*, *Actinomyces* sp., *Hormodendrum* sp., *Wojnowicia graminis*, *Ascochyta graminicola*. *Aspergillus niger* and *Monilia sitophilia* frequently grew from the plated tissue, and often to the exclusion of other fungi or bacteria. However, in most cases, the tissue yielded either *H. sativum* or *Fusarium* spp. or both.

In spite of the fact that signs of take-all were evident on occasional wheat plants in all experiments, and at certain stations were more or less pronounced, *O. graminis* was not definitely identified once from 47,000 odd plants plated out. Its absence may be accounted for partly by the presence of other micro-organisms that grow more rapidly in plate culture, by the rather unsuitable substrate that was used, by the slow growth-habit of this fungus, or by the disinfectant used.

From observations, during this study, the opportunities for *Fusarium* spp. and *H. sativum* to grow from the plated tissue would seem equally good. These fungi grow vigorously and are not very definitely antagonistic to each other, and any advantage in competition on the substrate used is usually with the *Fusarium* spp.

*Variation in Results*

It may be well to supply here, from the data, a typical example of the variation in percentage, of *H. sativum* and *Fusarium* spp., which occurred between the means of two similar crop sequences at a station in a given year. The results from material from the two continuous wheat sequences (treatments Nos. 5 and 6) at seven stations in 1930, will be used for the purpose. The average relative prevalence in percentage of *H. sativum*, *F. culmorum* and other species of *Fusarium* is indicated in Table I.

In both sequences, the variation with respect to *H. sativum* exceeded 10% at four of the seven stations, that is to say, this fungus appeared to be less prevalent in one of two identical rotations than the other at one station. A good example of this was at Olds, where the percentage was approximately 2 with treatment No. 6, and 19 with treatment No. 5. The cause for this variation is not known. However, there was fairly good agreement when the data from all stations were averaged. A similar situation existed with regard to *F. culmorum*, and to other species of this genus. At one of the stations the

TABLE I

PERCENTAGE ISOLATIONS OF *Helminthosporium sativum*, *Fusarium (culmorum* type) AND ALL *Fusarium* spp., FROM WHEAT OF TWO IDENTICAL SEQUENCES OF CONTINUOUS WHEAT AT VARIOUS STATIONS IN 1930

| Treatment | Stations* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mord. | I.H. | S.C. | Scott | Leth. | Olds | Verm. | Av. |
| *(H. sativum)* | | | | | | | | |
| 5. Cont. wheat | 37 | 62 | 46 | 63 | 53 | 19 | 49 | 47 |
| 6. Cont. wheat | 48 | 76 | 37 | 60 | 52 | 2 | 66 | 48 |
| *(F. culmorum)* | | | | | | | | |
| 5. Cont. wheat | 17 | 16 | 27 | 2 | 26 | 65 | 4 | 23 |
| 6. Cont. wheat | 9 | 10 | 31 | 12 | 30 | 79 | 2 | 25 |
| *(All Fusarium* spp.) | | | | | | | | |
| 5. Cont. wheat | 63 | 38 | 54 | 37 | 47 | 81 | 51 | 53 |
| 6. Cont. wheat | 52 | 24 | 63 | 40 | 48 | 98 | 34 | 52 |

**Following are abbreviations in above and in subsequent tables: Morden (Mord.), Manitoba; Indian Head (I.H.), Swift Current (S.C.), and Scott in Saskatchewan; and Lethbridge (Leth.), Olds and Vermilion (Verm.) in Alberta.*

variation was less, and in some cases probably within the error of the experiment. In the case of all *Fusarium* spp. the variation was greater than 11% at four of the seven stations. The most significant thing about this is that in the same year either *F. culmorum* or all species of *Fusarium* might be relatively scarce at one station and relatively abundant at another station in a similar sequence. This is well illustrated by the results from Vermilion and Olds.

### *Variation at all Stations each Year*

The two similar crop sequences, which were used to illustrate the variation in results occurring among stations in a given year, will be employed to indicate the yearly variation in the average results from all stations. The average relative prevalence of *H. sativum*, *F. culmorum* and other Fusaria is indicated in percentage in Table II.

TABLE II

AVERAGE YEARLY PERCENTAGE ISOLATIONS FROM ALL STATIONS OF *Helminthosporium sativum*, *Fusarium (culmorum* type) AND OTHER *Fusarium* spp. FROM WHEAT, OF TWO IDENTICAL SEQUENCES OF CONTINUOUS WHEAT

| | Sequence No. 5 | | | | | Sequence No. 6 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1928 | 1929 | 1930 | 1931 | 1932 | 1928 | 1929 | 1930 | 1931 | 1932 |
| *H. sativum* | 51 | 47 | 47 | 35 | 52 | 48 | 46 | 49 | 29 | 51 |
| *F. culmorum* | 8 | 28 | 23 | 24 | 24 | 11 | 31 | 25 | 29 | 24 |
| Other *Fusarium* spp. | 41 | 25 | 30 | 41 | 24 | 41 | 23 | 26 | 42 | 25 |

Except in 1931, the average prevalence of *H. sativum* and *Fusarium* spp. was relatively constant, varying fairly closely around 50% in each crop sequence. In 1931 the number of *Fusarium* spp. was greater than *H. sativum*

by about 30% in sequence No. 5 and by 42% in sequence No. 6. The average of the results during five years of each of the two sequences would suggest similar values for these fungi.

Comparisons of other crop sequences, where various crops precede wheat, cannot be made for obvious reasons. Even considerable variations might be expected in such instances, although it will be apparent later that the example just given fairly well illustrates the kind and range of variation in the data throughout the study.

## The Relative Prevalence of *H. sativum* and *Fusarium spp.* as Isolated from Wheat in Various Crop Sequences and Cultural Practices

Christensen (2) and others have shown the constant occurrence of *H. sativum* on the basal parts of barley, and Simmonds (3) the occurrence of *F. culmorum* on the crown and root tissue of oats. The crop sequences from which wheat plants were obtained for isolation purposes in this study are as follows, each with its respective reference number:—*Two-year rotations:* 1, summerfallow, wheat; 2, oats, wheat; 3, barley, wheat; 5, wheat, wheat; 6, wheat, wheat. *Three-year rotations:* 10, wheat, summerfallow, wheat; 11, wheat, summerfallow (manured), wheat; 12, summerfallow, summerfallow, wheat; 13, summerfallow, wheat, wheat; 14, summerfallow (manured), wheat, wheat; 15, oats, oats, wheat; 16, sweet clover, sweet clover, wheat; 17, western rye, western rye, wheat.

The foregoing rotations were at five of the Dominion Experimental Stations, and at two of the Alberta Schools of Agriculture.

TABLE III

THE AVERAGE PERCENTAGE ISOLATIONS*, AT VARIOUS STATIONS†, OF *Helminthosporium sativum* AND OF *Fusarium culmorum* FROM WHEAT WHICH FOLLOWED DIFFERENT CROPS

| Station | Mord. | | I.H. | | S.C. | | Scott | | Leth. | | Olds | | Verm. | | Av. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | Hs | Fc | Hs | Fc | Hs | Fc | Hs | Fc | Hs | Fc | Hs | Fc | Hs | Fc | Hs | Fc |
| Wheat after: | | | | | | | | | | | | | | | | |
| 1. S. fallow | 56 | 13 | 44 | 32 | 37 | 26 | 41 | 22 | 44 | 31 | 39 | 34 | 47 | 8 | 44 | 24 |
| 2. Oats | 57 | 14 | 48 | 30 | 37 | 27 | 29 | 29 | 45 | 35 | 18 | 51 | 46 | 9 | 40 | 28 |
| 3. Barley | 60 | 8 | 58 | 23 | 48 | 22 | 40 | 20 | 47 | 31 | 28 | 37 | 51 | 10 | 47 | 22 |
| 5. Wheat | 55 | 15 | 47 | 23 | 39 | 25 | 46 | 12 | 46 | 35 | 34 | 36 | 52 | 5 | 46 | 21 |
| 6. Wheat | 55 | 17 | 56 | 22 | 34 | 24 | 42 | 14 | 42 | 39 | 31 | 42 | 53 | 13 | 45 | 24 |
| 15. Two crops oats | 52 | 23 | 52 | 23 | 36 | 30 | 31 | 44 | 36 | 35 | 20 | 74 | 38 | 19 | 38 | 36 |
| 16. Two years s. clover | 51 | 17 | 46 | 27 | 36 | 19 | 40 | 27 | 36 | 36 | 8 | 79 | 36 | 4 | 36 | 30 |
| 17. Two years w. rye | 50 | 27 | 60 | 17 | 50 | 14 | 43 | 19 | 46 | 35 | 11 | 60 | 44 | 12 | 44 | 26 |
| Average | 54 | 17 | 51 | 25 | 39 | 23 | 39 | 23 | 43 | 35 | 24 | 51 | 46 | 10 | 43 | 26 |

**H. sativum and F. culmorum indicated by "Hs" and Fc," respectively.*

*†For Mord., I. H., Scott and Leth., 1928 to 1932, inclusive; for S.C., 1928 to 1930, inclusive; and for Olds and Verm., 1930 to 1932, inclusive.*

The average results in Table III would suggest at first that at some of the stations *H. sativum* was isolated more frequently from wheat after certain crops than after others. For example, at Morden the percentage was 60 after barley and 52 after two years of oats, and 56 following summerfallow, and only 55% following continuous wheat. However, at other stations it is

obvious that this relation is not maintained. *H. sativum* appeared to be more frequently isolated from wheat after barley than from wheat after other crops, this being most marked at Indian Head and Swift Current. However, as its relative prevalence was almost as great, or sometimes much greater, on wheat after summerfallow, or after oats, as it was on wheat after wheat or after barley, the differences would seem within the experimental error. The variation indicating the relative prevalence of all *Fusarium* spp. as affected by the crop sequence, may be explained similarly. Although the figures for this group are not given in Table III, they can be calculated readily. There appears to be a definite tendency at some stations for either *H. sativum* or the *Fusarium* spp. to predominate, regardless of crop sequence. At Morden, the former was in the ascendancy, while at Indian Head and Vermilion they were about equally prevalent.

Average data in Table III also suggest that the *culmorum* type of *Fusaria* was isolated more frequently at certain stations than at others. For example, at Vermilion and Morden it was consistently lower than at any other station, irrespective of the crop sequence. At other stations the proportion of *F. culmorum* to all *Fusarium* spp. appeared to be relatively higher. It is repeated here that, on account of the difficulty of correctly identifying *F. culmorum*, only marked differences would be significant.

That the variation obtained may be due to conditions at a station, and not to any particular crop sequence, is further suggested by the data in Table IV, where the average results for various sequences are given for each year at all stations. In general, the proportion of *H. sativum* to *Fusarium* spp. is very uniform for all crops, with one possible exception, *viz.*, wheat after oats, where the trend is for a greater proportion of *Fusarium* spp. However, greatest differences, which appear to be more consistent, occurred in certain years, for example, in 1931, where the isolations of *Fusarium* spp.

TABLE IV

THE YEARLY AVERAGE PERCENTAGE (FOR ALL STATIONS) OF ISOLATIONS* OF *Helminthosporium sativum* AND OF *Fusarium* spp., FROM WHEAT IN VARIOUS CROP SEQUENCES†

| Treatment | 1928 | | 1929 | | 1930 | | 1931 | | 1932 | | Av. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | H | F | H | F | H | F | H | F | H | F | H | F |
| Wheat after: | | | | | | | | | | | | |
| 1. Summerfallow | 50 | 50 | 41 | 59 | 49 | 51 | 34 | 66 | 49 | 51 | 45 | 55 |
| 2. Oats | 54 | 46 | 40 | 60 | 43 | 57 | 31 | 69 | 37 | 63 | 41 | 59 |
| 3. Barley | 56 | 44 | 50 | 50 | 48 | 52 | 37 | 63 | 49 | 51 | 48 | 52 |
| 5. Wheat | 51 | 49 | 47 | 53 | 47 | 53 | 35 | 65 | 52 | 48 | 46 | 54 |
| 6. Wheat | 48 | 52 | 46 | 54 | 49 | 51 | 29 | 71 | 51 | 49 | 45 | 55 |
| 15. Oats, oats | 43 | 57 | 41 | 59 | 41 | 59 | 27 | 73 | 41 | 59 | 39 | 61 |
| 16. S. clover, s. clover | 38 | 62 | 45 | 55 | 42 | 58 | 30 | 70 | 39 | 61 | 39 | 61 |
| 17. W. rye, w. rye | 52 | 48 | 54 | 46 | 48 | 52 | 33 | 67 | 49 | 51 | 47 | 53 |
| Average | 49 | 51 | 45 | 55 | 46 | 54 | 32 | 68 | 46 | 54 | 44 | 56 |

**H. sativum* and *Fusarium* spp. indicated by "H" and "F," respectively.*

*†Treatments Nos. 1, 2 and 3 are two-year rotations; Nos. 15, 16 and 17 three-year rotations; and Nos. 5 and 6, continuous wheat.*

predominated over those of *H. sativum* to a greater extent than for any year of the study. Similarly, in 1928, *H. sativum* was predominant, while in other years it was more or less secondary.

### *Effect of Manure*

In this study, isolations of *H. sativum* and *F. culmorum* were made from wheat in the four following three-year rotations:—10, wheat, summerfallow, wheat; 11, wheat, summerfallow (manured, 12 tons), wheat; 13, summerfallow, wheat, wheat; and 14, summerfallow (manured, 12 tons), wheat, wheat. The only difference between the first two rotations and between the last two rotations was that manure was applied to the summerfallow in one sequence in each instance. The infection rating on the third and fourth sequences, *viz.*, 13 and 14, where the isolations were made from the second crop of wheat, was 3.5 and 3.5, respectively, while for the first two, *viz.*, 10 and 11, it was 1.9 and 2.2.

TABLE V

THE EFFECT OF MANURE ON THE AVERAGE PERCENTAGE ISOLATIONS* OF *Helminthosporium sativum* AND OF *Fusarium* spp. FROM WHEAT. THE DATA APPLY TO CROP SEQUENCES AT MORDEN, INDIAN HEAD AND SCOTT, 1928 TO 1932, INCLUSIVE

| Stations | Mord. | | I.H. | | Scott | | Mean av. | |
|---|---|---|---|---|---|---|---|---|
| Treatment | H | F | H | F | H | F | H | F |
| Wheat after: | | | | | | | | |
| 10. Summerfallow | 46 | 54 | 53 | 47 | 45 | 55 | 48 | 52 |
| 11. Summerfallow (manured) | 50 | 50 | 55 | 45 | 36 | 64 | 47 | 53 |
| 13. Summerfallow, wheat | 52 | 48 | 62 | 38 | 52 | 48 | 56 | 44 |
| 14. Summerfallow (manured), wheat | 49 | 51 | 55 | 45 | 51 | 49 | 51 | 49 |

**H. sativum and Fusarium spp. indicated by "H" and "F," respectively.*

In Table V are shown the average percentages of *H. sativum* and *Fusarium* spp., obtained at three stations from 1928 to 1932, inclusive. It may be stated briefly that the results in this table indicate that the proportion of *H. sativum* to all *Fusarium* spp. was about the same where manure was applied as where it was not applied. The slight difference in either direction is probably not significant.

### *Effect of Cultural Practices*

Additional evidence that *H. sativum* and *Fusarium* spp. may be isolated from wheat by the method used, in about the same relative proportions, irrespective of crop sequence or cultural practice, is supplied by summarized data from that part of the experiment described in Part III (1) under "Cultural Practices" (treatments Nos. 21 to 42, inclusive). In this experiment the date, depth and rate of seeding wheat were each varied three ways, that

is to say, the seed was sown early, average and late; deep, average and shallow; and at a light, average and heavy rate. This experiment was duplicated on two rotations, namely "wheat, summerfallow, wheat"; and "summerfallow, wheat, wheat". The isolations in the latter instance were made from the second crop of wheat. The proportion of *H. sativum* to *Fusarium* spp., isolated using the various practices mentioned, is given in Table VI. Here it is apparent that the numbers of *H. sativum* and the *Fusarium* spp. isolated bear the same general ratio in each of the sequences at each of the three stations.

TABLE VI

THE AVERAGE PREVALENCE IN PERCENTAGE OF *Helminthosporium sativum** *and Fusarium* spp.* AS ISOLATED *A*, FROM THE SECOND WHEAT CROP AFTER SUMMERFALLOW, AND *B*, FROM THE FIRST WHEAT CROP AFTER SUMMERFALLOW, WHERE THE DATE, RATE, AND DEPTH OF SEEDING WERE VARIED

| Station | *A* | | | | | | | | *B* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I.H.† | | S.C.‡ | | Scott† | | Av. | | I.H.† | | S.C.‡ | | Scott† | | Av. | |
| | H | F | H | F | H | F | H | F | H | F | H | F | H | F | H | F |
| Date of seeding | | | | | | | | | | | | | | | | |
| Average | 51 | 49 | 50 | 50 | 42 | 58 | 48 | 52 | 54 | 46 | 39 | 61 | 46 | 54 | 46 | 54 |
| Late | 60 | 40 | 40 | 60 | 47 | 53 | 49 | 51 | 57 | 43 | 45 | 55 | 54 | 46 | 52 | 48 |
| Early | 54 | 46 | 42 | 58 | 54 | 46 | 50 | 50 | 51 | 49 | 51 | 49 | 51 | 49 | 51 | 49 |
| Rate of seeding | | | | | | | | | | | | | | | | |
| Average | 46 | 54 | 44 | 56 | 46 | 54 | 45 | 55 | 52 | 48 | 38 | 62 | 53 | 47 | 48 | 52 |
| Light | 53 | 47 | 41 | 59 | 49 | 51 | 48 | 52 | 55 | 45 | 50 | 50 | 58 | 42 | 55 | 45 |
| Heavy | 58 | 42 | 49 | 51 | 50 | 50 | 52 | 48 | 54 | 46 | 50 | 50 | 53 | 47 | 52 | 48 |
| Depth of seeding | | | | | | | | | | | | | | | | |
| Average | 60 | 40 | 40 | 60 | 47 | 53 | 49 | 51 | 57 | 43 | 45 | 55 | 54 | 46 | 52 | 48 |
| Deep | 55 | 45 | 51 | 49 | 46 | 54 | 51 | 49 | 57 | 43 | 39 | 61 | 56 | 44 | 51 | 49 |
| Shallow | 51 | 49 | 50 | 50 | 43 | 57 | 48 | 52 | 54 | 46 | 39 | 61 | 46 | 54 | 46 | 54 |
| Average | 54 | 46 | 45 | 55 | 47 | 53 | 49 | 51 | 55 | 45 | 44 | 56 | 52 | 48 | 50 | 50 |

**Indicated by "H" and "F," respectively.* †*A four-year average (1928-1931).*
‡*A three-year average (1928-1930).*

### *Effect of Climatic and Soil Factors*

So far in this study, the crop sequence or cultural practice did not seem to modify significantly the proportion of *H. sativum* to *Fusarium* spp. That soil or climatic factors may have some effect is suggested in Table VII where the yearly average preponderance for the respective fungi is indicated in percentage.

TABLE VII

THE EXCESS, IN PERCENTAGE, OF ISOLATIONS* OF *Helminthosporium sativum* AND *Fusarium* spp., OR *vice versa*, AT EACH STATION† DURING 1928 TO 1932, INCLUSIVE. DATA ARE BASED ON AVERAGE ISOLATIONS FROM WHEAT IN ALL SEQUENCES

| Station | 1928 | | 1929 | | 1930 | | 1931 | | 1932 | | Average | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | H | F | H | F | H | F | H | F | H | F | H | F |
| Mord. | 6 | | 14 | | 14 | | | 34 | 2 | | 0 | 0 |
| I.H. | 4 | | | 2 | 34 | | | 22 | — | — | 4 | |
| S.C. | 0 | 0 | | 10 | | 26 | — | — | — | — | | 12 |
| Scott | | 2 | | 12 | 14 | | | 26 | | 4 | | 6 |
| Leth. | 16 | | | 14 | | 6 | | 32 | | 44 | | 16 |
| Olds | — | — | — | — | | 74 | | 44 | 6 | | | 37 |
| Verm. | — | — | — | — | 4 | | | 24 | | 10 | | 10 |
| Av. | 5 | | | 5 | | 6 | | 30 | | 10 | | 9 |

**H. sativum and Fusarium spp. indicated by "H" and "F," respectively.*
*†Data are absent where dashes occur.*

In 1928 the isolations of *H. sativum* were greater than those of *Fusarium* spp. at Lethbridge, Indian Head, and Morden (16, 4 and 6%, respectively), but at Scott the difference was not significant. In 1929 the isolations were from 2 to 14% greater at all stations, except Morden, where those of *H. sativum* were greater (14%). In 1930, when final data from Olds and Vermilion were available, making seven stations in all, *H. sativum* was apparently more abundant at Indian Head, Scott, and Morden by 34, 14, and 14%, respectively, and at Vermilion by 4%, while the *Fusarium* spp. were in the majority at Olds by 74%, at Swift Current by 26%, and at Lethbridge by only 6%. The most striking difference was in 1931, when the isolations of *Fusarium* varied from 22 to 44% greater at the seven stations. In 1932 each organism appeared to be about equally abundant at all stations, except at Lethbridge, where the advantage for the *Fusarium* species was 44%. Data for Indian Head and Swift Current were not available for 1932.

Although it is impossible here to offer the correct explanation for the yearly variation indicated above, it would seem that the difference in soil and climate among the various stations might, either directly or indirectly, be responsible.

## Discussion

In view of the nature of the problem, and the necessarily indirect methods of analysis employed, only trends in certain directions rather than sharply defined results were anticipated. The fact that the tissue from which the platings were made was located in the soil, and therefore subject, not only to a range of soil conditions, but invasion by saprophytic as well as parasitic fungi, introduces conflicting factors. Then too, in artificial culture, the characteristic growth habits in association, of the fungi which may emerge from the internal tissue, not affected by the disinfectant, may tend to render difficult, and at times perhaps make impossible, the recognition of certain fungi. However it was pointed out earlier that, in general, both *H. sativum*

and the *Fusarium* spp. are about equally vigorous in growth, and fairly compatible. Moreover the regularity with which one or the other, and often both of these fungi emerged from the crown tissue used, suggests that a fairly accurate picture might be obtained. Obviously, without tests for pathogenicity, we have no idea regarding the possible significance of their presence, nor can the relative prevalence of these fungi in the tissue more than suggest their relative prevalence in the soil.

In this study the crown portions of 47,360 plants were cultured on potato sucrose agar. Either *H. sativum* or *Fusarium* spp., or both were found on 43,305 plants, which is very significant in view of the possible injury from toxic growth products and general parasitic effects in this tissue.

As far as could be ascertained from this study, the crop sequence or cultural practice used did not appear to affect significantly the relative prevalence of either *H. sativum* or *Fusarium* spp. in the crown tissue of wheat at a given station in any year. This is interesting in view of the fact that summerfallow, a crop of oats, sweet clover, or some non-susceptible crop, actually reduced the foot-rot damage on the following crop of spring wheats.

Perhaps the most significant result obtained was the indication that the climatic conditions, and possibly the soil, at a station, each year, determined the relative prevalence of *H. sativum* and the *Fusarium* spp.

## Acknowledgments

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## References

1. Broadfoot, W. C. Studies on foot and root rot of wheat. III. Effect of crop rotation and cultural practice on the development of foot rot of wheat. Can. J. Research, 10: 95-114. 1934.
2. Christensen, J. J. Studies on the parasitism of *Helminthosporium sativum*. Minnesota Agr. Expt. Sta. Tech. Bull. 11 : 1-42. 1922.
3. Simmonds, P. M. Studies in cereal diseases. III. Seedling blight and foot-rots of oats caused by *Fusarium culmorum* (W. G. Sm.) Sacc. Dept. Agr. Ottawa. Bull. 105 n.s. 1-43. 1928.

# *CYTOSPORA* INFECTION FOLLOWING FIRE INJURY IN WESTERN BRITISH COLUMBIA[1]

By John Dearness[2] and J. R. Hansbrough[3]

## Abstract

Data are given concerning the appearance of *Cytospora* spp. on 15 species of shrubs and trees following a light ground fire near D'Arcy, B.C. On 11 of the hosts was found a species of *Cytospora*, which is herein described under the name, *C. pulcherrima*. On three of the hosts was found an undetermined *Cytospora* with larger spores and darker, less delicate tendrils. On the one coniferous host present, Douglas fir, the only fungus present was determined as *C. friesii* Sacc.

The taxonomic importance of the study rests on the range of species of infected hosts which revealed a width hitherto unknown or at least unreported for a *Cytospora*.

In the north temperate latitudes there are few, if any, lignicolous plant species which are exempt from invasion by one or more parasitic or saprophytic members of the genus *Cytospora*. Thus, *Cytospora* spp. are common and sometimes highly injurious parasites of poplar (*Populus* spp.) (2, 5, 6, 7, 9, 10–14) and there are several published reports (4, 8, 15) of serious canker injury to fruit trees by the same or closely related species. The majority, however, of the species in this genus are regarded as saprophytes, or at worst, as parasites upon weakened living tissue. An example of this type of injury was observed by the junior writer and J. L. Mielke at D'Arcy, B.C.,* on May 31, 1931. The circumstances surrounding the case were thought to be of sufficient interest to merit a brief study of the conditions antecedent to the infection and of the fungi involved.

In the early spring of 1931 a light ground fire had run over an area of approximately one-tenth of an acre and had killed most of the herbaceous annuals and injured all of the shrubs and small trees. Of this latter group there were 15 different species present, and on all of them *Cytospora* spp. were fruiting near the bases of the living but weakened stems. The hosts, listed in the order of their apparent susceptibility to infection, were as follows: *Salix* sp., *Alnus tenuifolia* Nutt., *Populus trichocarpa hastata* Henry, *Philadelphus gordonianus* Lindl., *Cornus occidentalis* (T. and G.) Cov., *Crataegus brevispina* (Doug.) Hell., *Betula fontinalis* Sarg., *Pseudotsuga taxifolia* (LaM.) Britt., *Acer glabrum douglasii* (Hook.) Dipp., *Amelanchier florida* Lindl., *Grossularia divaricata* (Doug.) Cov. and Britt., *Ribes sanguineum* Pursh, *Rosa nutkana* Presl., *Sambucus glauca* Nutt., and *Rubus leucodermis* Doug.

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**D'Arcy is a stop on the Pacific Great Eastern Railway approximately 90 miles north of Vancouver, B.C.*

This susceptibility rating is based on the estimated bark area infected on the various species. No definite information could be obtained as to whether or not all of the host species were uniformly injured by the fire but from general observation such was thought to be the case. All of the shrubs and saplings on the area were rather badly scorched but in no instance had death resulted. Therefore, for example, if the willow and maple were apparently equally injured by the fire but the former was much more heavily infected by the fungi, then it was considered to be more susceptible to such invasion.

The typical cirri, or spore tendrils, of the genus *Cytospora* were very noticeable on all of the scorched plants except the Douglas fir, and were particularly conspicuous on the willow and alder saplings where they hung in moss-like appendages, three to four inches in length.

Collections of the fungi on all 15 hosts were made and sent to the senior author for critical study and determination.

Allescher (1) gives descriptions of 171 species of *Cytospora* reported from Central Europe, many of whose descriptions are practically duplicated, or even triplicated, in their important features except host habitat. It is reasonable to expect that many of these so-called species will, when their life histories are fully known, be reduced to synonomy or varietal rank. The variation in the thickness, firmness and chemical nature of the bark of the different hosts may be expected to cause some corresponding variation in the morphology of a single fungus growing upon them.

If no two of the 15 hosts enumerated above had grown within miles of each other it is probable that instead of one species of *Cytospora* appearing on 11 of them, there might have been at least a few supposedly different species. The identical conditions under which these examples were initiated and developed give them unusual taxonomic importance. The question arises whether or not the scorching of the bark is a favoring or possibly a necessary condition of its growth.

As indicated above, on 11 of the 15 host species there was found the same *Cytospora* which is described below as a new species.

## *Cytospora pulcherrima*

*Cytospora pulcherrima* sp. nov., but possibly a stage of *Valsella pulcherrima* (E. and E.) Berl. (3).

Pustules conic, rather thinly and evenly scattered, less frequently in small groups, concolorous but gradually darkening as the underlying stromata progress toward maturity, showing a whitish granular substance around the perforation at the apex. Stromata erumpent, seated in the cortex, not reaching the wood, not circumscribed by a dark line; flesh pallid at first, becoming dark gray, 1–1.3 mm. in diameter at base; pycnidial chambers few to many, radiate-crowded, opening into a common, black, minute ostiole which when mature enough to discharge conidia can be seen with a hand lens as a dark speck in the white granular apex. Conidia allantoid, hyaline, minute, 3.5–4

by 0.75 $\mu$, issuing in protected places as pale amber-colored, hair-like tendrils, elsewhere as darker corkscrews, horns or beads. Conidiophores filiform, fasciculate, or subdendriform; forming a layer over the hymenial lining of the chambers, 15–22 $\mu$ deep.

On Salicaceae; *Salix* sp., *Populus trichocarpa hastata:* Betulaceae; *Betula fontinalis, Alnus tenuifolia:* Cornaceae; *Cornus occidentalis:* Rosaceae; *Amelanchier florida, Crataegus brevispina, Rosa nutkana:* Saxifragaceae; *Philadelphus gordonianus:* Aceraceae; *Acer glabrum douglasii:* Caprifoliaceae; *Sambucus glauca.*

*Type locality.* D'Arcy, British Columbia.

*Distribution.* Known only from the type locality and from near Northport, Washington.

*Specimens examined.* Herbarium of the Division of Forest Pathology, United States Department of Agriculture: Collections as follows made at D'Arcy, B.C., by J. R. Hansbrough and J. L. Mielke. On *Salix* sp. 40,844. On *Alnus tenuifolia*, 40,845. On *Populus trichocarpa hastata*, 40,846. On *Cornus occidentalis*, 40,847. On *Crataegus brevispina*, 40,848. On *Philadelphus gordonianus*, 40,849. On *Betula fontinalis*, 40,850. On *Acer glabrum douglasii*, 40,852. On *Amelanchier florida*, 40,853. On *Rosa nutkana*, 40,856. On *Sambucus glauca*, 40,857.

Herbarium of J. Dearness: Parts of all the above collections under one group number, 7,859 (Composite type). On *Salix* sp., Pepoon Lake, Northport, Wash., coll. E. E. Hubert.

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On all of the hosts at D'Arcy except the *Rosa* and *Sambucus*, the *Cytospora* was closely associated with a Valsella stage. Mature discharged ascospores of this *Valsella* were not observed but their size and shape in the ascus were determined and the fungus was identified as *V. pulcherrima.*

The *Valsella* at first closely tesselates the bark with black-margined disks, each centered with a speck of whitish granular substance. The regularity and prettiness of these disks at this stage probably suggested the specific name *pulcherrima*. Later they become conical pustules, with few to many crowded ostioles, not rising above the ruptured bark. In most of the pustules there is more or less whitish ectostromatic tissue overlying the perithecia and surrounding the ostioles.

In 1929 Prof. E. E. Hubert of the School of Forestry, Moscow, Idaho, sent the senior author a *Valsella*, which the latter referred to *V. pulcherrima*, and also a *Cytospora*, both collected on *Salix* sp. on the shores of Pepoon Lake, near Northport, Wash. Prof. Hubert reported the fungi as killing many clumps of the willow. These two forms cannot now be separated from the specimens from D'Arcy, B.C. The tentatively assumed relationship between the *Cytospora* and the *Valsella* remains to be proved but the assumption that they are related is so strong that the authors risk giving this important "Imperfect" the possibly provisional name of *C. pulcherrima.*

On three of the remaining four hosts, namely, *Grossularia divaricata*, *Ribes sanguineum* and *Rubus leucodermis*, there was present a second and entirely different *Cytospora* which has not been identified because of the absence of any perfect stage associated with it. This fungus has larger spores, 6–8 × 2 $\mu$, and darker, redder, less delicate cirri. In addition to the three above-listed hosts, it was occasionally found along with *C. pulcherrima* on the 11 hosts upon which that fungus was collected.

On the one remaining host, *Pseudotsuga taxifolia*, the only fungus present was identified as *Cytospora friesii* Sacc. Considering the ubiquitous occurrence of some species of *Cytospora* it is significant that there was in this case no crossing-over of a species from a deciduous to a coniferous host, or *vice versa*.

## References

1. ALLESCHER, A. Die Pilze Deutschlands, Oestereichs und der Schweiz. Rabenhorst's Kryptogamen-Flora, 6 : 563-620; 7 : 867-870. 1901.
2. BROWN, J. G. *Cytospora* canker, a disease destructive to cotton-woods and poplars. Ariz. Agr. Exptl. Sta. Timely Hints for Farmers, No. 138 : 1-4. 1922.
3. ELLIS, J. B. and EVERHART, B. M. New species of North American fungi from various localities. Proc. Acad. Nat. Sci. Philadelphia, p. 144. 1893.
4. FISHER, D. F. and REEVES, E. L. A *Cytospora* canker of apple trees. J. Agr. Research, 43 : 431-438. 1931.
5. HARTLEY, C. and HAHN, G. G. Notes on some diseases of aspen. Phytopathology, 10 : 141-147. 1920.
6. HUBERT, E. E. Observations on *Cytospora chrysosperma* in the Northwest. Phytopathology, 10 : 442-447. 1920.
7. LEACH, J. G. Poplar canker. Eleventh annual report of the State Entomologist. Colorado State Agr. Exp. Sta. Cir. 28 : 46. 1920.
8. LEONIAN, L. H. Studies on the *Valsa* apple canker in New Mexico. Phytopathology, 11 : 236-243. 1921.
9. LONG, W. H. An undescribed canker of poplars and willows caused by *Cytospora chrysosperma*. J. Agr. Research, 13 : 331-343. 1918.
10. MOSS, E. H. Observations on two poplar cankers in Ontario. Phytopathology, 12 : 425-427. 1922.
11. POVAH, A. H. W. An attack of poplar canker following fire injury. Phytopathology, 11 : 157-165. 1921.
12. SANFORD, G. B. The *Cytospora* disease of Russian poplar. Rep. Dom. Botanist for 1930. Ottawa. pp. 36-37. 1931.
13. SCHREINER, E. J. Two species of *Valsa* causing disease in *Populus*. Am. J. Botany, 18 : 1-29. 1931.
14. SCHREINER, E. J. The role of disease in the growing of poplar. J. Forestry, 29 : 79-82. 1931.
15. STEVENS, F. L. An apple canker due to *Cytospora*. Ill. Agr. Exptl. Sta. Bull. 217 : 367-379. 1919.

# MEASUREMENTS OF THE SURFACE TENSION OF CARBON TETRACHLORIDE AT LOW TEMPERATURES[1]

By T. Alty[2] and G. F. Clark[3]


## Abstract

The variation of the surface tension of carbon tetrachloride with temperature has been determined with considerable accuracy between +12° C. and −10° C.


## Introduction

At temperatures higher than room temperature the surface tension of carbon tetrachloride has been determined by a number of observers, but at lower temperatures only a few isolated determinations (3, 4, 5) have been made. Accurate values of the surface tension over a range of temperature in the neighborhood of 0° C. were required in connection with other work in progress in this laboratory, and as these were not otherwise available, measurements of the surface tension have been made in the temperature range between +12° C. and −10° C. The present paper gives the results obtained.

## Experimental

The two most accurate methods for the determination of surface tension are the capillary rise and the drop weight methods. The latter was found more convenient for the present work and was used throughout.

Harkins and Brown (2) have shown that the mass ($m$ grams) of the drop which falls from a circular tip of radius $R$ cm. is given by the formula

$$mg = 2\pi R\gamma f\left(\frac{R}{V^{\frac{1}{3}}}\right) \tag{1}$$

where $\gamma$ is the surface tension of the liquid in dynes per cm., $V$ is the volume of the drop in cc. and $f\left(\frac{R}{V^{\frac{1}{3}}}\right)$ is a correction factor whose values are tabulated for different values of $\left(\frac{R}{V^{\frac{1}{3}}}\right)$ by Harkins and Brown.

In order that Equation (1) shall apply accurately, the tip on which the drop is formed must be perfectly circular and free from flaws and its lower surface, from which the drop hangs, must be perfectly horizontal. In addition, the rate of formation of the drop must be sufficiently slow. If due attention is given to these points, very accurate values of the surface tension may be obtained by this method.

The arrangement of apparatus used was quite similar to that of Harkins and Brown. As they have given a detailed description of it in their paper (1),

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*Contribution from the Physical Laboratories, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.*
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this need not be repeated here. The drops fall into a weighing bottle of known mass which is supported inside a water-tight container. The latter is immersed in a large thermostat so that the weighing bottle acquires the temperature of the thermostat but is not wetted by the thermostat liquid. When temperature equilibrium is established a number of drops of tetrachloride are allowed to form slowly on the tip and are collected in the weighing bottle which is then removed from the thermostat, stoppered and weighed.

The important part of the apparatus is the tip on which the drops are formed. In the present experiments a glass tip was used. This was prepared as suggested by Harkins by inserting a piece of glass capillary tubing in a lathe and running the latter at high speed. A flat plate, on which was placed fine wet carborundum powder, was held against the side of the rotating glass and the side ground until the glass had a uniformly circular cross section. The side was then carefully polished and the end of the tube ground flat and perpendicular to the side. When ready for use no flaws in the circular edge of the tip could be detected on examination in a low power microscope.

At temperatures above 0° C. water was used as the thermostat liquid; at lower temperatures this was replaced by a mixture of snow and calcium chloride.

The carbon tetrachloride was the best obtainable commercially and was further purified. It was washed several times with pure sulphuric acid and then with distilled water. The washing was repeated with a solution of sodium hydroxide and finally with distilled water once more. Calcium chloride was then added to the tetrachloride and the container left in a shaker for 24 hr. in order to remove most of the water. The drying process was completed by the addition of pure sodium. Finally the liquid was filtered and distilled, the middle fraction alone of the distillate being used. This portion was redistilled and only the tetrachloride distilling off within 0.02°C. of the true boiling point was used in the experiments.

If the empty weighing bottle is fitted over the dropping tip at room temperature and the apparatus is then immersed in a thermostat at a lower temperature, there will be an appreciable condensation of vapor in the bottle. Consequently the mass of liquid found in the bottle at the end of the experiment will be the sum of the masses of the fallen drops and that of the condensation. The true drop weight can therefore not be determined directly from the weight of the liquid.

The correction for the condensation clearly will depend both on the initial temperature of the apparatus and also on the temperature of the thermostat. The initial temperature of the apparatus was kept constant in all the experiments by immersing the water-tight container, containing the weighing bottle and tip, in a water bath at 25° C. The apparatus remained in this bath until temperature equilibrium was established and was then transferred to the cold thermostat for the experiment proper. In order to eliminate the varying effect of the vapor condensation at different thermostat temperatures the experiment was performed in two portions. In the first, the mass ($m_1$ gm.)

of five drops plus the condensation was determined; in the second, the mass ($m_2$ gm.) of 30 drops plus the condensation was obtained. Subtraction of the two results at any given thermostat temperature then gives the true weight of 25 drops at this temperature. In practice, the large heat capacity of the water-tight container and its contents made it rather difficult to reproduce the lower temperatures exactly for a whole series of experiments. For this reason the mass $m_1$ was measured at a large number of different temperatures and the results represented graphically. A second similar series of experiments gave $m_2$, the mass of 30 drops plus the condensation, as a function of the temperature. From the two curves so obtained, the true mass of 25 drops could be read off at any desired temperature.

There are two difficulties peculiar to work at temperatures below room temperature. As soon as the apparatus is taken from the thermostat, the weighing bottle is removed from the dropping tip and tightly stoppered to prevent the escape of vapor. The liquid inside is at the temperature of the thermostat, which is considerably below room temperature. Consequently there is an immediate deposit of water vapor on the outside of the weighing vessel when the temperature of the latter is below the dew point. This may seriously interfere with the weighings.

Again when the bottle is stoppered, the temperature of the liquid inside is low and its vapor pressure is small. As the liquid temperature rises, the total pressure inside becomes greater than atmospheric pressure and there is a tendency for vapor to leak out of the container. The weighing bottles used had ground glass stoppers which were carefully reground to give as perfect a fit as possible so as to minimize the effect of this loss of vapor. With these precautions, the leak was very steady and was barely large enough to be noticed in weighing.

It was further observed that the water vapor, condensed on the outside of the weighing bottle, evaporated again very rapidly once the temperature of the bottle approached that of the room and that about one and a half or two minutes after removing the bottle from the thermostat all trace of the water vapor had vanished from the bottle.

The bottles were therefore weighed in the following standard manner. After removal from the thermostat, the bottle was stoppered immediately and placed on a metal plate so that its temperature rose uniformly and fairly quickly to that of the room and the water vapor evaporated from its surface. The bottle was weighed exactly two minutes after it had been taken from the thermostat. By this time its outer surface was perfectly free from water so that the weight obtained was the true weight of the bottle and the contained liquid. Further, if the time between removal from the thermostat and the weighing of the bottle is the same in all cases, the small amount of carbon tetrachloride vapor lost by leakage will be very approximately the same for an experiment with five drops as for one with 30 drops, so that no appreciable error will appear in the drop weight deduced from the two curves. All the masses given in the graphs are therefore those of the liquid contained in the

weighing bottle two minutes after removal from the thermostat. It is believed that this procedure eliminates any error due to condensation on the outside of the bottle.

## Results

The radius of the dropping tip was measured by means of a low power microscope. The mean value of 20 measurements gives

$$R = 0.19726 \text{ cm.},$$

the average error of the measurements being 0.00019 cm.

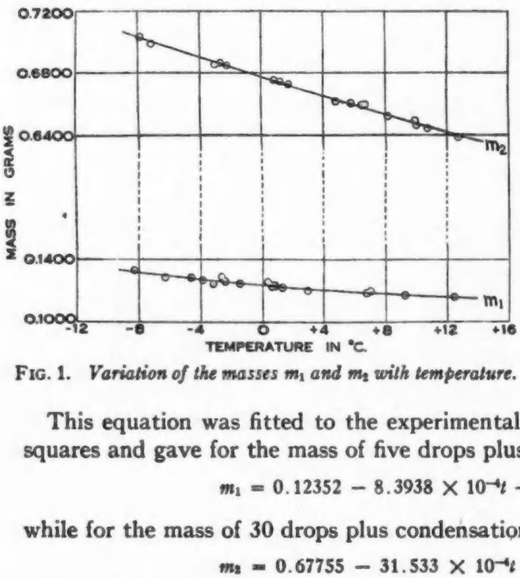


FIG. 1. *Variation of the masses $m_1$ and $m_2$ with temperature.*

The time of formation of a drop when allowed to form freely on the tip was about four minutes.

It will be seen from Fig. 1 that the graphs of $m_1$ and $m_2$ as functions of the temperature are very nearly linear and over the short range of temperature used in these experiments, the results can be represented by an equation of the type

$$m = a + bt + ct^2.$$

This equation was fitted to the experimental data by the method of least squares and gave for the mass of five drops plus the condensation

$$m_1 = 0.12352 - 8.3938 \times 10^{-4}t + 1.9168 \times 10^{-5}t^2 \tag{2}$$

while for the mass of 30 drops plus condensation it gives

$$m_2 = 0.67755 - 31.533 \times 10^{-4}t + 1.7944 \times 10^{-5}t^2 \tag{3}$$

In Fig. 1 the circles represent the actual experimental points while the curves drawn are those given by Equations (2) and (3).

Finally by subtraction of Equation (2) from Equation (3) we have the mass of 25 drops and hence the mass ($m$ gm.) of one drop in the form

$$m = 0.022161 - 9.2557 \times 10^{-5}t - 4.896 \times 10^{-8}t^2 \tag{4}$$

The values of $m$ have been calculated from Equation (4) at intervals of 1° between +12° C. and −10° C. The surface tensions are deduced therefrom by direct application of the equation

$$\gamma = \frac{mg}{2\pi R f\left(\frac{R}{V^{1/3}}\right)},$$

the correction factor $f\left(\frac{R}{V^{1/3}}\right)$ being obtained from Harkins' table.

The results of the calculation are given in Table I.

TABLE I

RESULTS OF CALCULATIONS

| $t$, °C. | $m$, gm. | Dynes per cm. | $t$,° C. | $m$, gm. | Dynes per cm. |
|---|---|---|---|---|---|
| +12 | .021043 | 27.80 | + 1 | .022068 | 29.14 |
| +11 | .021137 | 27.92 | 0 | .022161 | 29.27 |
| +10 | .021230 | 28.04 | − 1 | .022253 | 29.39 |
| + 9 | .021324 | 28.17 | − 2 | .022346 | 29.51 |
| + 8 | .021417 | 28.29 | − 3 | .022438 | 29.63 |
| + 7 | .021506 | 28.41 | − 4 | .022532 | 29.75 |
| + 6 | .021604 | 28.54 | − 5 | .022623 | 29.87 |
| + 5 | .021697 | 28.66 | − 6 | .022714 | 29.99 |
| + 4 | .021791 | 28.78 | − 7 | .022806 | 30.11 |
| + 3 | .021883 | 28.90 | − 8 | .022898 | 30.24 |
| + 2 | .021976 | 29.02 | − 9 | .022990 | 30.36 |
| | | | −10 | .023082 | 30.48 |

The only data with which the above measurements may be compared directly are those of Harkins and Cheng (3) who give values of 28.05 dynes per cm. at +10° C. and 29.38 dynes per cm. at 0° C. It will be seen that their value at +10° C. is practically identical with that given above, while the agreement at 0° C. is not quite so good. They do not give the details of the purification of their material and with the exception of the two values quoted, their measurements were all made at higher temperatures outside the range of the present experiments. Richards and Carver (5) using extremely pure carbon tetrachloride made accurate measurements of the surface tension at 20° C. This temperature is higher than any used in the present work, but it is interesting to note that extrapolation of the Equation (4) to 20° C. gives $\gamma = 26.80$ dynes per cm. which compares very closely with Richards' value of 26.77 dynes per cm.

## Acknowledgment

The authors wish to thank Dr. T. Thorvaldson and Dr. V. Vigfusson of the Department of Chemistry for advice as to the purification of the carbon tetrachloride.

## References

1. HARKINS, W. D. and BROWN, F. E. J. Am. Chem. Soc. 38 : 246-252. 1916.
2. HARKINS, W. D. and BROWN, F. E. J. Am. Chem. Soc. 41 : 499-524. 1919.
3. HARKINS, W. D. and CHENG, Y. C. J. Am. Chem. Soc. 43 : 35-53. 1921.
4. HARKINS, W. D., CLARK, G. L. and ROBERTS, L. E. J. Am. Chem. Soc. 42 : 700-712. 1920.
5. RICHARDS, T. W. and CARVER, E. K. J. Am. Chem. Soc. 43 : 827-847. 1921.

# THE SOUND FIELD OF MEMBRANES AND DIAPHRAGMS

## I. THE ANGULAR DISTRIBUTION OF THE SOUND PRODUCED BY A LARGE DIAPHRAGM[1]

By R. Ruedy[2]


## Abstract

The amplitudes of the sound waves set up by a thin circular plate clamped at the edge and vibrating with circular and radial nodes, have been calculated for distances which are large with respect to the radius of the disk (loudspeaker). The results are compared with those obtained at various frequencies when a rigid oscillating piston set into an infinite wall is used as a source or reproducer of sound. The two main differences between the vibrating plate and piston are the much greater amplitudes obtained in certain directions when the diaphragm is used, even though the displacement at the centre of the disk may be the same in both cases, and the strong tendency to send the sound sideways instead of directly forward. While the diaphragm shares these properties to a certain extent with the stretched membrane, it displays them in a more practical range. The theoretical frequencies at which these features are found to be most pronounced are in agreement with the values found by experiment.


## Introduction

When studying surfaces and materials which are used as reproducers or sources of sound, a short rigid oscillating piston set into an infinite wall is commonly chosen as the basis of comparison. For ordinary purposes the radius of the disk or flat cone is about a decimetre so that up to at least 250 cycles per sec., the point where the wave-length in air has dropped to 133 cm., the dimensions of the disk are small compared with the wave-length. Below this frequency, which comprises only the lowest range of the vibrations reproduced in the ordinary telephone talking circuit (250 to 3,000 cycles per sec.), the disk acts more or less like a point source giving divergent waves with, at a given distance, the same amplitude whatever the direction. Above this frequency, however, up to 10,000 cycles per sec., the highest frequency for which modern transmitting circuits are designed, interference effects appear, and the sound becomes more and more concentrated along a few narrow beams. Indeed, for short waves, the variations in the distances of a given point from the various elements of the vibrating surface are of the order of the wave-length itself and the impulses received differ in phase except in the cases of those points which lie far away upon lines parallel to the normal to the disk (12, 16–18).

The to-and-fro motion given to the reproducing surface—which is of the same type whatever the kind of sound concerned—approaches the behavior of the rigid piston. There are, however, not many musical instruments which approximate this artificial source (1).

On the other hand, in order to get, with moderate magnetic or electrical forces, amplitudes of practical value, it is necessary to keep the mass of the

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moving system small and the surface thin, this of course at the expense of stiffness. The rigid non-resonant piston thus becomes a thin plate, and the consequence is that at the higher frequencies all the disks and cones used in speakers vibrate in sections separated by circular or radial nodes. Recent investigations undertaken in various laboratories have actually established the fact that loudspeakers commonly possess fundamental natural frequencies of but a few hundred cycles per sec., and cease to be rigid above this point, that is, in the range where the focusing effect of the rigid disk begins (2, 3, 8–12, 19–22, 24). Moreover, in at least one type of loudspeaker, namely, in the electrostatic type of reproducer, a thin membrane is caused to vibrate in an extended alternating electric field in such a way that there no longer remains any resemblance to the rigid piston at any frequency (7, 13, 23). Even walls in buildings behave as large diaphragms when transmitting sound from one room to the other.

In view of these conditions the surfaces of loudspeakers may be expected to combine the properties of pistons and diaphragms, and it is of interest to determine what properties are possessed by the sound field created by diaphragms or thin plates and what is the power emitted, computing the values to the same degree of precision as has been attained with the rigid piston.

## The Transverse Vibrations of Diaphragms (Thin Circular Plate Clamped at the Edge)

Among vibrating plane surfaces the diaphragm, a very thin circular plate clamped along the edge, as far as mathematical analysis is concerned, is the two-dimensional development of the thin rod in the same way that the drum-head or membrane is related to the string. Plates of appreciable thickness form the transitional stage between oscillating plane surfaces and solid bodies vibrating in three dimensions. Once the surface has been deformed and released, the stiffness of the thin plate suffices to bring it back into its former shape. The equations of motion of a surface element, under the uniform external force $N_0\epsilon^{i\sigma t}$, are as follows (4, 6, 14, vol. I, p. 358):

$$\Delta^4 w + \frac{12s(1-\mu^2)}{Eh^2}\frac{\partial^2 w}{\partial t^2} = \frac{12(1-\mu^2)}{Eh^3} N_0\epsilon^{\sigma i t} ,$$

where

$$\Delta^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial^2}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \phi^2} ,$$

and $w$ is the elongation normal to the surface, $h$ is the thickness of the plate $E$ the modulus of elasticity of the material, $s$ the specific gravity and $\mu$ is Poisson's ratio for the material.

In the case of resonance ($N_0 = 0$) and assuming sinusoidal displacements, each element given by its polar coordinates $(r, \phi)$ performs a simple harmonic oscillation normal to the thin plate according to the law

$$w = \left[J_n(\kappa r) - \frac{J_n(\kappa a)}{J_n(i\kappa a)} J_n(i\kappa r)\right](A_n \cos n\phi + B_n \sin n\phi)\,\epsilon^{ipt} ,$$

where

$$p = 2\pi f = \kappa^2 a^2 \frac{h}{2a^2}\sqrt{\frac{E}{3s(1-\mu^2)}}$$

for free or clamped plates when $f$ is the resonance frequency of vibration. In the case of the membrane, the motion is given by the equation

$$w = J_n(\kappa r)\,(A_n \cos n\phi + B_n \sin n\phi)e^{i\omega t}\ .$$

Moreover, by virtue of the boundary conditions for the clamped plate, only those values of $\kappa$ are admissible for which the Bessel functions $J$ satisfy the relation

$$\frac{J_n(\kappa r)}{J_n(i\kappa r)} = \frac{dJ_n(\kappa r)/dr}{dJ_n(i\kappa r)/dr} \qquad \text{for } r = a \text{, the radius of the disk,}$$

or

$$\frac{J_n(\kappa r)}{J_{n-1}(\kappa r)} = \frac{J_n(i\kappa r)}{iJ_{n-1}(i\kappa r)} \qquad \text{for } r = a.$$

A number of solutions $\kappa_{n0}a,\ \kappa_{n1}a,\ \kappa_{n2}a \ldots\ \kappa_{n\nu}a$, and therefore a number of resonance frequencies $f_{n\nu}$, result for each $n$, as shown by Table I, the overtones of the thin plate progressing more rapidly to higher values than those of the membrane and producing a somewhat more harmonious sound (Fig. 1). Neglecting $\mu^2$ (which usually lies between 0 and 0.25) the resonance frequency may be written

$$f_{n\nu} = 0.046\,\frac{\kappa^2_{n\nu}\,a^2}{a^2}\,hC\,,$$

for instance, $f_{00} = 0.466\ hC_m/a^2{}_{dm}$ , with $C_m$ , the velocity of sound varying from about 500 m. for cork to 5,000 m. for aluminium and iron, and it follows that for a disk of 10 cm. radius, resonance is produced at short wavelengths unless the thickness of the plate be kept very small ($h < 0.1$ cm.). Interference effects are therefore to be expected as a rule in the space facing the vibrating thin plate clamped along the circumference and set into an infinite wall. They are liable to enhance the uneven distribution of sound which is caused by parts of the diaphragm vibrating in phase opposition as

TABLE I

SOLUTIONS OF THE DIAPHRAGM EQUATION $J_n(\kappa a)J'_n(i\kappa a) = J_n(i\kappa a)J'_n(\kappa a)$

| | $\nu = 0$ | $\nu = 1$ | $\nu = 2$ | $\nu = 3$ | $\nu = 4$ | $\nu$ |
|---|---|---|---|---|---|---|
| $n = 0$ | 3.1961 | 6.3064 | 9.4395 | 12.577 | 15.716 | $(\nu + 1)\,\pi$ |
| 1 | 4.611 | 7.7993 | 10.958 | 14.108 | — | $(\nu + 3/2)\,\pi$ |
| 2 | 5.9056 | 9.1967 | 12.402 | 15.579 | — | $(\nu + 2)\,\pi$ |
| 3 | 7.143 | 10.537 | 13.795 | — | — | $(\nu + 5/2)\,\pi$ |
| $n$ | — | — | — | — | — | $\left(\nu + 1 + \frac{n}{2}\right)\pi$ |

($n$ = *number of nodal diameters,* $\nu$ *number of nodal circles*).

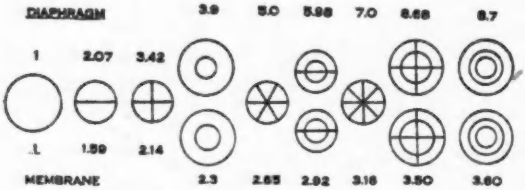


FIG. 1. *Overtones of diaphragm and membrane for similar modes of vibration (fundamental = 1).*

compared to the rest of the surface. The number of nodal diameters is particularly important in this respect. When there is an even number of diameters upon which the elements remain permanently at rest, any two points symmetrically situated with regard to the centre move in exact phase. When the number is odd, the two symmetrical points have the same amplitude, but move in different directions.

From the equation giving the displacement of the surface elements the velocity of the points along the direction normal to the disk can be expressed as follows:

$$w' = \dot{w}(r,\phi)\epsilon^{ipt} = \left[J_n(\kappa r) - \frac{J_n(\kappa a)}{J_n(i\kappa a)}J_n(i\kappa r)\right](A'_n \cos n\phi + B'_n \sin n\phi)\epsilon^{ipt}$$

where $\quad A'_n = ipA_n$ and $B'_n = ipB_n$ .

### Pressure Amplitude and Direction

The problem is to compute for the distant point $P$ the pressure $p$ of the air and the velocity $\dot{v}$ resulting from the vibrations of the diaphragm set into an infinite wall. The shortest method is first to ascertain Rayleigh's velocity potential $\Phi$ at the point selected:

$$\Phi = -\frac{1}{2\pi}\int_S \dot{w}(r,\phi)\,\epsilon^{ipt}\frac{\epsilon^{-ikR}}{R}dS ,$$

where $R$ is the distance of the point $P$ from the various surface elements, and $k=2\pi/\lambda$. In the present case, point $P$ is chosen so far away that the lines connecting it with the surface are all parallel to each other.

The centre of the circular diaphragm is taken as the origin of a system of polar co-ordinates (Fig. 2). A perpendicular from the surface element $dS$ at the point $S(r, \phi)$ upon the line $OP$ joining the distant point $P(r, \phi, y)$ to the origin intersects $OP$ at the distance $l$ from the origin. If the distance $OP$ is made equal to $R_0$, then $PS$ equals $R_0-l$, and the distance from the point $S'$ symmetrically situated with respect to the origin is equal to $R_0+l$ where, with $\rho$ as the angle between $OS$ and $OP$,

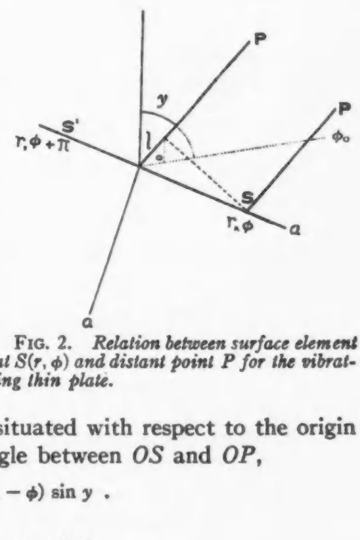


FIG. 2. *Relation between surface element at $S(r, \phi)$ and distant point $P$ for the vibrating thin plate.*

$$l = r\cos\phi = r\cos(\phi_0 - \phi)\sin y .$$

Therefore

$$\Phi = -\epsilon^{ipt}\frac{\epsilon^{-ikR_0}}{2\pi R_0}\int_S \dot{w}(r,\phi)\,\epsilon^{\pm ikl}dS .$$

Here the value of $R_0$ is constant and much larger than $l$ as long as we are interested only in the effects produced at remote points along a chosen direction.

When surface elements which lie symmetrically with respect to the centre vibrate with the same amplitude and phase, that is, when $w(r, \phi)$ equals

$w(r, \phi+180)$, and $n$ is even, corresponding pairs of points may be combined and give

$$\Phi = -\epsilon^{ipt}\frac{\epsilon^{-ikR_0}}{\pi R_0}\int_0^r\int_0^\pi r\,dr\,d\phi\,\dot{w}(r,\phi)\cos kl\ ,$$

and in the case of opposite phases ($n$ an odd number)

$$\Phi = -i\epsilon^{ipt}\frac{\epsilon^{-ikR_0}}{\pi R_0}\int_0^r r\,dr\int_0^\pi \dot{w}(r,\phi)\sin\left(kr\sin\gamma\cos(\phi_0-\phi)\right)d\phi\ ,$$

where in both cases

$$\dot{w} = \left[J_n(\kappa r) - \frac{J_{n\nu}(\kappa a)}{J_{n\nu}(i\kappa a)}J_n(i\kappa r)\right]\left[A'_{n\nu}\cos n\phi + B'_{n\nu}\sin n\phi\right]$$

Pressure $P$ and velocity $v$ at the point $(r, \phi)$ follow from the relations $P = -\rho\partial\Phi/\partial t$ (where $\rho$ is the density of the air) and $v = -\partial\phi/\partial R$, giving a velocity component in phase and a component out of phase with the pressure which for even values of $n$ are:

$$v = \frac{ik}{\pi R_0}\epsilon^{ipt}\epsilon^{-ikR_0}\int_0^r\int_0^\pi r\,dr\,d\phi\,\dot{w}(r,\phi)\cos kl\ -\ \frac{1}{\pi R_0^2}\epsilon^{ipt}\epsilon^{-ikR_0}\int_0^r\int_0^\pi r\,dr\,d\phi\,\dot{w}(r,\phi)\cos kl.$$

For computing the integral entering into the velocity potential $\Phi$, advantage may be taken of the following relations:

$$\cos(g\cos\phi) = J_0(g) - 2J_2(g)\cos 2\phi + 2J_4(g)\cos 4\phi - \ldots.$$

$$\sin(g\cos\phi) = 2J_1(g)\cos\phi - 2J_3(g)\cos 3\phi + 2J_5(g)\cos 5\phi\ \ldots$$

and as

$$\int_0^\pi \cos n\phi\cos(g\cos\phi)\,d\phi = \pi J_n(g),\ \text{if } n \text{ is even;}\quad \text{zero, if } n \text{ is odd.}$$

$$\int_0^\pi \sin n\phi\sin(g\cos\phi)\,d\phi = \text{zero, if } n \text{ is even;}\quad \pi J_n(g),\ \text{if } n \text{ is odd,}$$

hence, by using $(\phi_0-\phi)$ as the new variable:

$$\int_0^\pi \cos n\phi\cos(g\cos(\phi_0-\phi))\,d\phi = \pi\cos n\phi_0\,J_n(g),\ \text{if } n \text{ is even,}$$

$$\int_0^\pi \sin n\phi\sin(g\cos(\phi_0-\phi))\,d\phi = \pi\sin n\phi_0\,J_n(g),\ \text{if } n \text{ is odd,}$$

$$\int_0^\pi \sin n\phi\cos(g\cos(\phi_0-\phi))\,d\phi = \text{zero, if } n \text{ is even,}$$

$$\int_0^\pi \cos n\phi\sin(g\cos(\phi_0-\phi))\,d\phi = \text{zero, if } n \text{ is odd.}$$

Finally

$$\pi\int_{0}^{r=a} dr\, r\, J_n(\kappa r) J_n(kr \sin y)$$

$$= \frac{\pi a^2}{\kappa^2 a^2 - (ka \sin y)^2} \left(ka \sin y\, J_{n-1}(ka \sin y)\, J_n(\kappa a) - \kappa a\, J_{n-1}(\kappa a)\, J_n(ka \sin y)\right)$$

$$\pi\int_{0}^{r=a} dr\, r\, J_n(i\kappa r)\, J_n(kr \sin y)$$

$$= \frac{-\pi a^2}{\kappa^2 a^2 + (ka \sin y)^2} \left(ka \sin y\, J_{n-1}(ka \sin y)\, J_n(i\kappa a) - i\kappa a\, J_{n-1}(i\kappa a)\, J_n(ka \sin y)\right)$$

$$= \frac{-\pi a^2}{\kappa^2 a^2 + (ka \sin y)^2} \frac{J_n(i\kappa a)}{J_n(\kappa a)} \left(ka \sin y\, J_{n-1}(ka \sin y)\, J_n(\kappa a) - \kappa a J_{n-1}(\kappa a)\, J_n(ka \sin y)\right).$$

With the two terms combined and taking into account the boundary condition the final result of the integration, apart from the factor

$$-\,2\kappa^2 a^2\, a^2 \epsilon^{-ikR_o}\, \epsilon^{ipt} A'_{n\nu}/R_o$$

is given by

$$\Phi \parallel \cos n\phi_o \frac{ka \sin y\, J_{n-1}(ka \sin y)\, J_n(\kappa_{n\nu} a) - \kappa_{n\nu} a\, J_{n-1}(\kappa_{n\nu} a)\, J_n(ka \sin y)}{(\kappa_{n\nu} a)^4 - (ka \sin y)^4}$$

for even values of $n$, and by the same expression except that the cosine is replaced by the sine function and $A$ by $B$ for odd values of $n$.

This result may be compared with the expression valid for the clamped circular membrane for which $J_n(\kappa a) = 0$, and

$$\Phi \parallel \cos n\phi_o \frac{\kappa_{ns} a\, J_{n-1}(\kappa_{ns} a)\, J_n(ka \sin y)}{(\kappa_{ns} a)^2 - (ka \sin y)^2}$$

for even values of $n$, apart from the factor $-a^2 \epsilon^{-ikR_o}\, \epsilon^{ipt} A'_{ns}/R_o$, and, finally, with

$$\Phi = -\,a^2 \epsilon^{ipt} \frac{\epsilon^{-ikR_o}}{R_o} \dot{w}_o \frac{J_1(ka \sin y)}{ka \sin y}\quad ,$$

for the rigid piston, where $\dot{w}_o$ is the velocity amplitude of the solid elements, the same over the entire surface of the piston. The pressure at any distant point is found from $\Phi$ by multiplying with the factor $ip$ and the density $\rho$ of the air.

## Discussion of Results

For a diaphragm of a given material, provided only that its thickness is sufficiently small, the wave-length corresponding to the fundamental frequency $f_{oo}$ will be much larger than the radius $a$; in other words, $ka$ and $ka \sin y$ become negligible compared to $\kappa_{oo} a$ . However, by virtue of the formula determining the natural frequencies

$$p_{n\nu} = 2\pi f_{n\nu} = \frac{2\pi c}{\lambda_{n\nu}} = 0.29\, \frac{\kappa^2_{n\nu} a^2}{a^2}\, hC$$

(where $c$ is the velocity of sound in air), the rate at which $k = 2\pi/\lambda$ grows when progressively higher overtones are chosen is determined by the square of $\kappa_{n\nu}$ so that there exists a frequency at which $ka \sin y$ becomes equal to $\kappa a$. Up to this stage, and for a given angle, the denominator of $\Phi$ has kept falling

steadily except in the neighborhood of the points for which the numerator reduces to zero, and the pressure amplitude at the point $P$ has passed from negligible to large values. Beyond this point it drops again. The increase with frequency will be more rapid the larger the angle $y$.

The practical bearing which these results may have depend on the relation between $k$ and $\kappa$:

$$k = \frac{2\pi}{\lambda} \approx 0.29\, \kappa^2_{n\nu} a^2 \frac{hC}{a^2 c}.$$

Taking as an average value for $C$ that of brass, namely, 3,580 m. per sec., or of oak or beechwood, 3,300 to 3,400 m. per sec., with the radius of the disk as before equal to 10 cm. and neglecting $\mu^2$, then at resonance

$$k_{n\nu} = \frac{2\pi}{\lambda_{n\nu}} = 0.029\,(\kappa_{n\nu}a)^2 h \longrightarrow 0.029\,\pi^2 \left(\nu + 1 + \frac{n}{2}\right)^2 h$$

or

$$k_{n\nu} \longrightarrow 0.29 \left(\nu + 1 + \frac{n}{2}\right)^2 h\,.$$

The corresponding values are shown in Table II.

TABLE II

VALUES OF $2\pi/\lambda$ AT THE RESONANCE FREQUENCIES FOR AN AVERAGE DIAPHRAGM

($C/c \approx 10$ AND $a$ = 10 cm.)

| | Number of nodal circles | | | | |
|---|---|---|---|---|---|
| | $\nu = 0$ | $\nu = 1$ | $\nu = 2$ | $\nu = 3$ | $\nu = 4$ |
| $k_{0\nu}$ | $0.295\,h$ | $1.149\,h$ | $2.573\,h$ | $4.67\,h$ | $7.03\,h$ |
| $\kappa_{0\nu}a$ | 3.196 | 6.306 | 9.44 | 12.58 | 15.72 |
| $k_{1\nu}$ | $0.614\,h$ | $1.758\,h$ | $3.472\,h$ | $5.75\,h$ | |
| $\kappa_{1\nu}a$ | 4.61 | 7.8 | 10.96 | 14.11 | |
| $k_{2\nu}$ | $1.01\,h$ | $2.4\,h$ | $4.44\,h$ | $7.02\,h$ | |
| $\kappa_{2\nu}a$ | 5.91 | 9.12 | 12.40 | 15.58 | |
| $k_{3\nu}$ | $1.78\,h$ | | | | |
| $\kappa_{3\nu}a$ | 7.14 | | | | |

For a given $\nu$ the values of $ka$ and $\kappa_{n\nu}a$ become equal when $n$ satisfies the relation $\left(\frac{n}{2}+\nu\right)ha \geqq 10$. For practical purposes ($h<0.1$ cm.) whenever the radius of the diaphragm exceeds several centimetres, the value of $\kappa a$ is always appreciably larger than $ka \sin y$ in the case of all the simpler forms of vibration ($n$ or $\nu < 4$), and with all the common materials the great maximum of pressure amplitude is reached only in the ultrasonic region. With paper, however, resonance frequencies seem to be pronounced at $n>10$ (19). Below this value the amplitudes keep on increasing at each successive resonance frequency, the growth being most rapid for large angles with the normal.

In addition, there is a variation of the sound pressure amplitude as the angle $y$ with the normal is changed. For a given resonance frequency the

value of the numerator depends only on the value of $ka \sin y$, being, for $n=0$, for instance, equal to $-ka \sin y\ J_1(ka \sin y)\ J_o(\kappa a) + \kappa a\ J_1(\kappa a)\ J_o(ka \sin y)$, or varying between $\kappa_{o\nu}a\ J_1(\kappa_{o\nu}a)$ and $+\ \kappa_{o\nu}a\ J_1(\kappa_{o\nu}a)\ J_o(\kappa a) - ka\ J_o(\kappa_{o\nu}a)\ J_1(ka)$ as $y$ changes from 0 to 90°. For the fundamental resonance frequency and the first overtones the denominator retains the same sign. Beyond $\kappa a$ or $ka \sin y$ equal to 2.4 in the case of $J_o$ and 3.8 in the case of $J_1$, the Bessel functions change sign as the angle is varied, and as the terms grow at different rates they cancel for certain angles $y$. Thus, for the third overtone there is no change in pressure along the direction which forms an angle of about 40° with the normal; for the fourth overtone ($\kappa a = 15.72$, $ka = 7.03$) the silent zones lie between 20 and 30°, and between 50 and 60°; for the fifth overtone between 10 and 20, 30 and 40, and 60 and 70°. For progressively increasing values we may write

$$\kappa_{o\nu}a = (\nu + 1)\,\pi \text{ and } \kappa_{1\nu}a = \left(\nu + \frac{3}{2}\right)\pi\ ,$$

and

$$J_o(\kappa_{o\nu}a) = \frac{\sin\,(\nu+1)\,\pi + \cos\,(\nu+1)\,\pi}{\pi\sqrt{\nu+1}} = \pm\frac{1}{\pi\sqrt{\nu+1}}\ .$$

$$J_1(\kappa_{o\nu}a) = \frac{\sin\,(\nu+1)\,\pi - \cos\,(\nu-1)\,\pi}{\pi\sqrt{\nu+1}} = \mp\frac{1}{\pi\sqrt{\nu+1}}\ .$$

so that

$$\Phi_{o\nu} \parallel \frac{\pm\ ka \sin y\ J_1(ka \sin y) \mp\ (\nu+1)\pi\ J_o(ka \sin y)}{\pi\sqrt{\nu+1}\,((\kappa+1)^4\pi^4 - (ka \sin y)^4)} \cos n\phi\ ,$$

with the pressure amplitude dropping to zero for all values for which $(\nu+1)\pi = ka \sin y\ J_1(ka \sin y)/J_o(ka \sin y)$, in which formula $ka \sin y$ varies between 0 and $ka$. We have then as many silent zones as there are zero values of $J_1(ka \sin y)$ below $J_1(ka)$, evidently fewer, the smaller $a$ and $h$, rules which are already valid for overtones of low order.

Finally, owing to the presence of the factor $\cos n\phi_o$ (or $\sin n\phi_o$ when $n$ is odd) in the formula, no sound pressure changes develop in the planes perpendicular to the diaphragm and passing through the nodal diameters, a conclusion which is in agreement with the experimental results. The larger the number of nodes passing through the centre, the smaller the intensity in the forward direction along the normal axis, because of the higher order of the Bessel function $J_n(ka \sin y)$ which must then be used.

## Comparison with the Angular Distribution Produced by a Membrane or Piston

In order to give an illustration of the angular distribution of pressure amplitude produced by the diaphragm, the formula has been applied to a thin plate vibrating with zero, two or four circular nodes ($n=0$), assuming $a=10$ and $h=0.1$ cm. The corresponding resonance frequencies are therefore $f_{oo} = 150$, $f_{o2} = 1{,}340$ and $f_{o4} = 3{,}740$ cycles per sec. (Figs. 3 and 4). Although the higher frequency is still far below that at which the highest possible maximum of pressure is obtainable (at $ka = \kappa a \approx 31$, or $f$ about 166,000), the

pressure amplitudes exceed the values for the rigid piston at practically every large angle, provided, of course, that the velocity amplitude of the central point is the same in both cases.

The power emitted sideways is most remarkable, and in distinct contrast to the behavior of the rigid piston which tends to throw the sound directly forward. This point would seem to warrant further experimental tests. At a frequency of 3,740 cycles per sec. the sound emitted by a rigid piston of 10 cm. radius lies almost entirely within the angle $\psi = \sin^{-1} 2 \times 10^4 / af \approx 30°$.

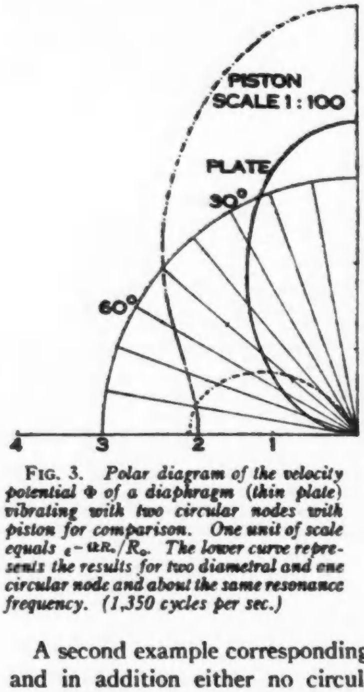


FIG. 3. *Polar diagram of the velocity potential $\Phi$ of a diaphragm (thin plate) vibrating with two circular nodes with piston for comparison. One unit of scale equals $\epsilon^{-ikR_0}/R_0$. The lower curve represents the results for two diametral and one circular node and about the same resonance frequency. (1,350 cycles per sec.)*

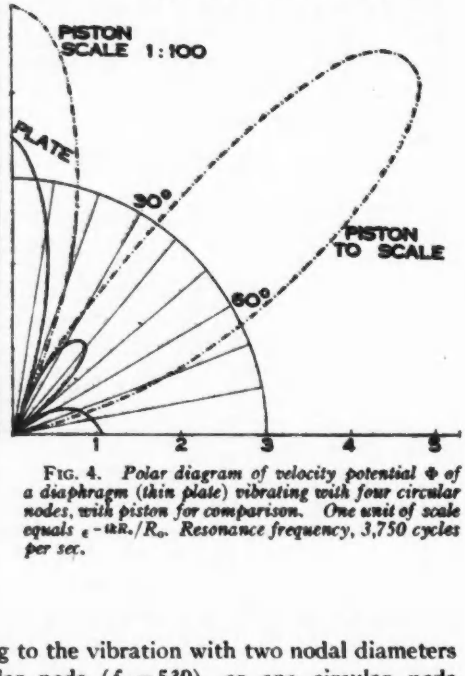


FIG. 4. *Polar diagram of velocity potential $\Phi$ of a diaphragm (thin plate) vibrating with four circular nodes, with piston for comparison. One unit of scale equals $\epsilon^{-ikR_0}/R_0$. Resonance frequency, 3,750 cycles per sec.*

A second example corresponding to the vibration with two nodal diameters and in addition either no circular node ($f_{20} = 530$), or one circular node ($f_{21} = 1{,}260$) and three circular nodes ($f_{23} = 3{,}700$ cycles), or practically the same frequencies as before, shows that at all these frequencies there is little variation of the sound pressure amplitude when the angle with the normal increases from about 50 to 90°.

The advantages to be derived from the fact that a circular vibrating surface behaves as a flexible structure are, therefore, not only increased output, at certain resonance frequencies, but more even distribution of sound, even though the wave-length be smaller than the radius.

The thin circular plate clamped at the edge shares these properties to a certain extent with the clamped membrane. There exists, however, the difference that, owing to the relation,

$$2\pi f_{mn} = \frac{2\pi c}{\lambda_{mn}} = \kappa_{mn}\sqrt{\frac{T}{\sigma}}$$

or

$$k_{ns}a = \kappa_{ns}a\sqrt{\frac{T}{\sigma}} \ ,$$

where $\kappa_{ns}$ now is one of the solutions of the equation $J_n(\kappa a)=0$, the values of $ka$ and $\kappa a$ increase at the same rate, so that a stretched membrane either gives high sound pressure at all resonance frequencies (when $k=\kappa$), or, when the wave-length corresponding to the lowest natural frequency is larger than the diameter of the disk, negligible sound pressures at all frequencies.

Now the resonance frequencies $f_{ns}$ of the membrane are given by

$$f_{ns} = \frac{\kappa_{ns}a}{2\pi a}\sqrt{\frac{T}{\sigma}}$$

where $Tdl$ is the tension in dynes across a straight line of length $dl$ drawn anywhere upon the membrane and $\sigma$ the mass per sq. cm. A membrane sending out at resonance a wave-length comparable to its own dimensions (3,300 cycles per sec. or $\lambda=10$ cm.) would require too high a tension to be safely applied to a membrane of 10 cm. radius, so that the high outputs are not obtained in practical cases when structures resembling clamped membranes are used as sources or reproducers of sound.

Another difference between membrane and diaphragm is the position of the silent zones. In the case of the circular membrane, no sound pressure develops along directions for which $J_n(ka \sin y)=0$, or for a given frequency, along as many directions as there are nodal circles, the angles being, however, the same for a given $n$, apart from their number. For a diaphragm, on the other hand, the silent zones are given by (when $\kappa a \neq ka \sin y$)

$$\frac{J_n(ka \sin y)}{ka \sin y \, J_{n-1}(ka \sin y)} = \frac{J_n(\kappa_{ns}a)}{\kappa_{ns}a \, J_{n-1}(\kappa_{ns}a)} \ ,$$

a relation more difficult to satisfy than the condition found for the membrane, and giving a smaller number of silent zones when $n$ is large.

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The results obtained have been used for computing the total power radiated by membranes and diaphragms. The results for very strong vibrations will have to be corrected by terms taking into account air-damping and radiation resistance.

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## References


1. Backhaus, H. Z. Physik, 72 : 218-225. 1931.
2. Benecke, H. Z. tech. Physik, 13 : 481-483. 1932.
3. Benecke, H. Wireless Eng. 10 : 257. 1933.
4. Carrington, H. Phil. Mag. 50 : 1261-1264. 1925.
5. Crandall, I. B. Theory of vibrating systems and sound. D. Van Nostrand. New York. 1926.
6. Debye, P. Ann. Physik, 25 : 819-823. 1908.
7. Edelman, P. E. Proc. Inst. Radio Eng. 19 : 256-267. 1931.
8. McLachlan, N. W. Proc. Roy. Soc. Lond. 122 : 604-609. 1929.
9. McLachlan, N. W. Wireless World, 29 : 106-109, 164-166, 193-195. 1931.
10. McLachlan, N. W. Phil. Mag. 13 : 115-143. 1932.
11. McLachlan, N. W. Phil. Mag. 14 : 1012-1025. 1932.
12. McLachlan, N. W. Ann. Physik, 15 : 422-439. 1932.
13. Neumann, H. and Trendelenburg, F. Z. Hochfr. Technik, 37 : 149-151. 1931.
14. Rayleigh, Lord. The theory of sound. Macmillan and company. London. 2 v. 1929.
15. Schulze, F. A. Ann. Physik, 24 : 785-822. 1907.
16. Stenzel, H. Elek. Nachr. Tech. 4 : 239-253. 1927.
17. Stenzel, H. Elek. Nachr. Tech. 7 : 87-99. 1930.
18. Stenzel, H. Ann. Physik, 7 : 947-982. 1930.
19. Strafford, F. R. W. Wireless Eng. 10 : 141. 1933.
20. Strutt, M. J. O. Ann. Physik, 11 : 129-140. 1931.
21. Strutt, M. J. O. Proc. Inst. Radio Eng. 19 : 839-850. 1931.
22. Turner, P. K. J. Inst. Elec. Eng. 69 : 591-622. 1931.
23. Vogt, H. Z. tech. Physik, 12 : 632-639. 1931.
24. Voigt, B. Z. tech. Physik, 12 : 76-85. 1931.